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AFAPL-TR-65-24

DEVELOPMENT OF GAS-ENTRAINED POWDER LUBRICANTS FOR HIGH SPEED-AND HIGH-TEMPERATURE OPERATION OF SPUR GEARS

Technical Report AFAPL-TR-65-24
May 1965

Air Force Aero Propulsion Laboratory
Research and Technology Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

Project No. 3044, Task No. 304402

(Prepared under Contract No. AF33(657)-8625
By the Stratos Division of the Fairchild
Hiller Corporation, Bay Shore, New York;
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FOREWORD

This report was prepared by Stratos Division, Fairchild Hiller Corporation, under USAF Contract No. AF33(657)-8625. The contract was initiated under Project No. 3044, "Aerospace Lubrication", Task No. 304402, "Advanced Propulsion Lubrication Engineering." The work was administered under the direction of the Fuels and Lubricants Branch, Air Force Aero Propulsion Laboratory, Research and Technology Division with Mr. G. A. Beane, IV, acting as project engineer.

This report covers work conducted from June 1962 to January 1964.

Technical advisory services on this program were rendered by Battelle Memorial Institute.

The writer wishes to acknowledge the contributions to the program of Mr. John Cirillo, and Mr. Vernon Richards. The assistance of Mr. Frank Hebscher in the conduct of tests in the Stratos Division Laboratories is also acknowledged.

The writer desires to add a note of appreciation to Mr. Alvin A. Schlosser for his advice and guidance which added materially in the progress of this program.

ABSTRACT

The feasibility of adapting powder lubricants to the operation of gears during relatively long periods of time under extreme environmental conditions was established. In addition to the lubricant study, parallel investigations were conducted on gear materials and methods of dispensing powder lubricants.

Significant achievements of this program are listed below.

1. A pair of 5 DP spur gears, manufactured from M-50 tool steel, had operated for 98-1/2 hours at a speed of 7400 rpm, load of 1000 pounds per linear inch of tooth face, and temperature cycled from room temperature to 900° F.

2. Evaluations of fine-pitch (12/14 DP) superalloy and tool-alloy steel gears were conducted at speeds to 15,500 rpm, temperatures in excess of 1000° F, and loads to 1000 pounds per linear inch of tooth face.

3. All high-temperature evaluations performed during this program used a graphite plus cadmium oxide powder mixture as the gear lubricant. An air carrier was used to deliver the powder to the gear set.

PUBLICATION REVIEW

This technical report has been reviewed and is approved.

Blackwell C. Dunnam

BLACKWELL C. DUNNAM, Chief
Fuels and Lubricants Branch
Air Force Aero Propulsion Laboratory

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SECTION 1
INTRODUCTION

This program was initiated to develop lubricants and lubrication techniques and to evaluate materials that would permit spur gears to operate at temperatures to 1200° F, speeds to 15, 000 rpm, and high loads utilizing the lubricants and delivery methods developed.

The most successful lubricant used in this study was a mixture of graphite and cadmium oxide.

The ideal gear material was not found during this program that would sustain 100 hours of gear operation at temperatures in the range from 1000 to 1200° F and at speeds of 15, 000 rpm. The M-50 tool steel gears performed well at a speed of 7400 rpm and a temperature of 900° F for 98-1/2 hours during the Phase I investigations. Haynes Stellite No. 6B gears, in the Phase II investigations were operated at a speed of 10, 350 rpm and in the temperature range from 1000 to 1100° F for a period of 48-1/2 hours.

Two types of gears fabricated from several types of steel were used in the tests which were conducted in two phases. Phase I gear sets had a hunting-tooth arrangement in which a 5-diametral-pitch 15-tooth gear meshed with a 5-diametral-pitch 16-tooth gear. These gears were made of case-hardened steels and tool steels. Phase II gears each had 39 teeth having a pitch of 12/14 and were made from nickel-base and cobalt-base alloys.

A fine-pitch gear had to be designed for high-temperature operation using powder lubrication. A complete stress analysis of the gear teeth is given together with comparative details of several other tooth designs of different diametral pitch to show the reasons for the choice of 39 of 12/14 stub form. This complete design report is included in the appendix to this report.

Prior research program have developed lubricants operating over the range or room temperature to 1200° F. The endurance of angular-contact-type bearings operating at temperatures to 1200° F and speeds to 50,000 rpm while lubricanted by powdered and gaseous type lubricants formed the basis for lubricant selection, bearing design, and bearing material specifications.

A significant achievement was the operation of a cobalt-base alloy angular-contact-type ball bearing of 20 mm bore size for 70 hours using powder-type lubricants entrained in gas carriers with speeds cycled from 5000 to 30,000 rpm and temperatures to 1200° F under 100-pound thrust loading and 10-pound radial loads. The work conducted during these programs are reported in the following reports:

WADC TR 59-790
WADD TR 60-732
WADD TR 60-732 Part II

Manuscript released by author February 1965 for publication as an RTD Technical Report.

SECTION 2
POWDER LUBRICATION OF GEARS - TEST APPARATUS

DESCRIPTION OF TEST RIG

The high-temperature gear-test rig shown in Figures 1 and 2 was used in all gear-lubrication evaluations. The test rig operates on the four-square, or closed power circuit, principle with the test gears being permanently positioned on a 3.250-inch center distance.

The mechanical power distribution circuit consists of two gear boxes (test box and power-return box) which are connected by two parallel shafts. The circuit is driven by a 5-hp electric motor that is capable of speeds up to 3500 rpm. The power is transferred from the motor to the power circuit via pulleys and a timing belt. A selection of pulleys allows speeds up to 30,000 rpm to be achieved. The simplicity of the circuit using the four-square principle of power distribution permits a large amount of power amplification because the power supply is required only to overcome the friction loads in the circuit. Loading of the test gears is accomplished by locking in a torque or twist at a flanged coupling in the shafting. The load is applied statically with a lever and weight system.

Rig bearings and service (power-return) gears are oil lubricated. Relatively small bearing and service-gear loads are imposed upon the test rig when operated without the test gears being installed.

TEST HEAD HEATERS

Gear heating has been accomplished by a Chromalox rod unit rated at 2250 watts. Its 6-foot length has been fitted into the gear-heater housing and positioned to efficiently apply heat to the test gears. The test rig was modified following test G-117 to provide 4500 watts of heater capacity by the installation of a second 2250-watt rod heater. The increased temperature capacity allowed for testing at gear temperatures to approximately 1200° F.

SHIELDS

It was determined during the initial gear-testing evaluations that shielding should be installed in the test gear chamber. Shield No. 1 shown in Figure 3 was used to confine the lubricant powder to an effective area around the gear mesh in test G-100B. The metal strip has little effect in limiting the lubricant to the mesh area. Therefore, Shield No. 2 was assembled to the test head with Shield No. 1 in test G-101, as shown in Figure 4. The lubricant film that formed on the gears during the test was spotty and uneven, so in an attempt to improve this condition, Shield No. 3 was combined with Shield No. 1 as shown in Figure 5. As the temperature approached 1000° F in later tests, it was indicated that a more efficient shielding would be required. In test G-104A, Shield No. 4 (Figure 6) was installed with Shields No. 1 and No. 3 in an effort to improve lubricant flow to the gear mesh. This proved to be our most successful approach to the shielding problem and was used in all subsequent tests.

INSTRUMENTATION

Chromel-alumel thermocouples were used to measure temperature at appropriate rig and test locations. A thermocouple was located in the endplate of the test-gear

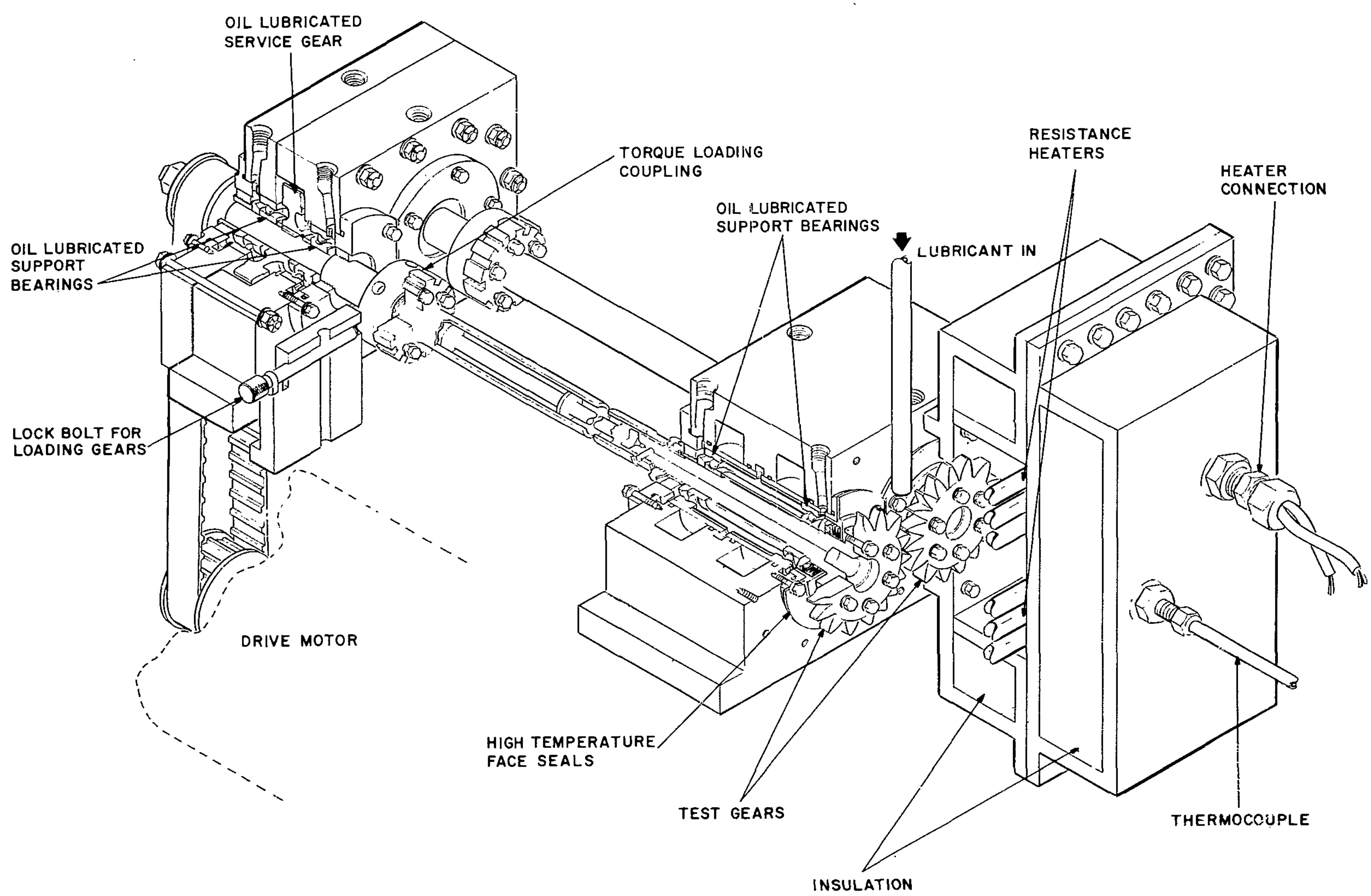


Figure 1. Isometric Cutaway View of Stratos High-Temperature Gear Test Rig

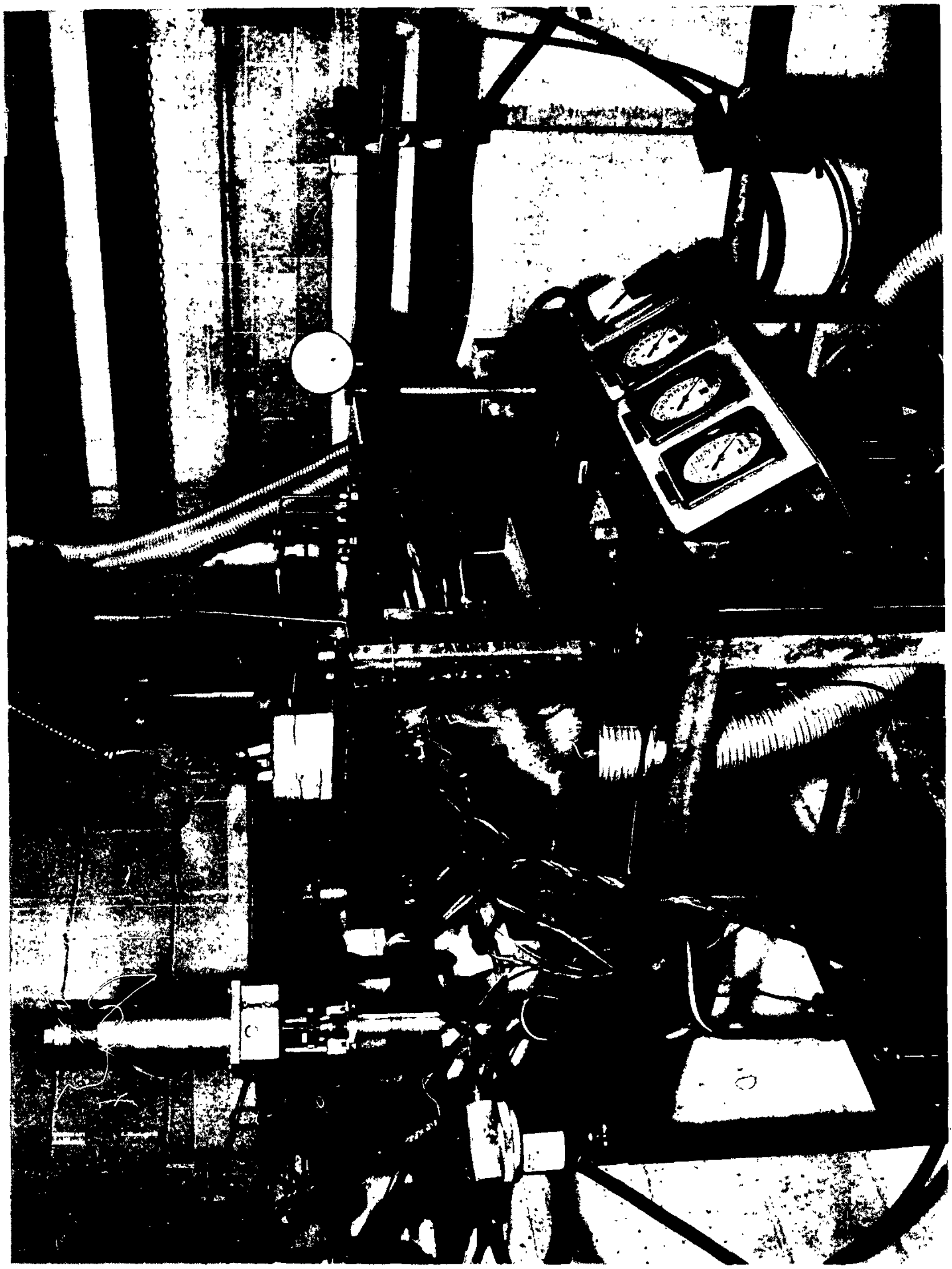


Figure 2. Three-Quarter View of Stratos High-Temperature Gear Test Rig

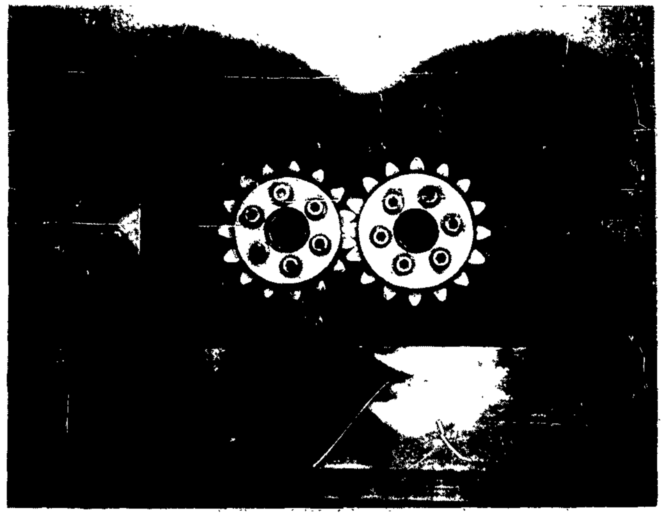


Figure 3. Shield No. 1 Installed in Test Head

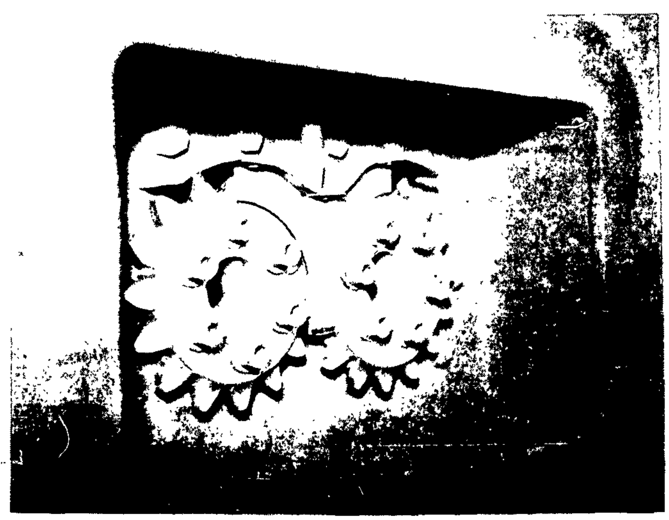


Figure 4. Shields No. 1 and No. 2 Installed in Test Head

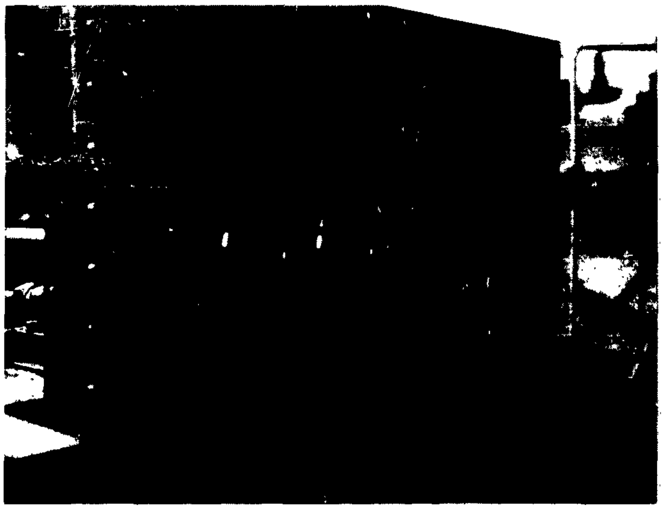


Figure 5. Shields No. 1 and No. 3 Installed in Test Head

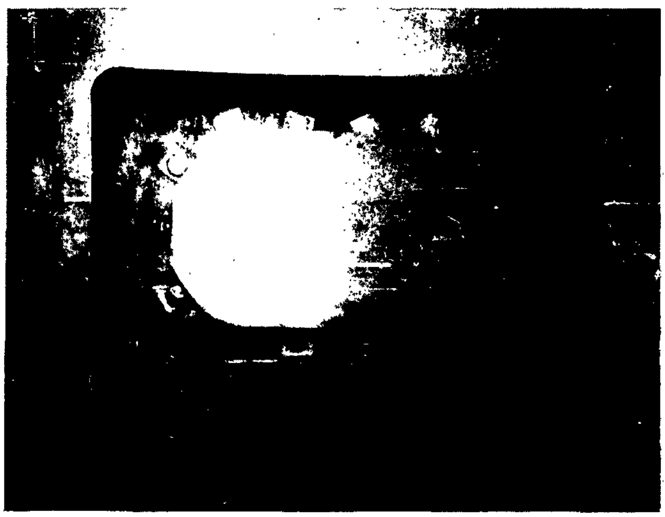


Figure 6. Shield No. 4 Installed with Shields No. 1 and No. 3 in Test Head

chamber about 1/8-inch from the teeth of a test gear. The temperature monitored by the thermocouple is referred to in the discussion as "tooth-vicinity temperature". A Stroboconn timing and scanning unit indicated the speed of the lubricator air-motor shaft. Rig shaft speed was measured with a hand tachometer. The rig motor current was indicated in the drive motor circuit.

LUBRICATION TECHNIQUES

Powder lubrication of the test gears was provided in the test apparatus by a variable speed gear-feed lubricator that was developed during the ball-bearing lubrication program. The lubricator is driven by an air motor at a maximum speed of 600 rpm. An extension of the air-motor shaft drives an agitator that is located in the lubricant supply cannister. A two-stage worm gear reduction is used to decrease the speed of the scoop-equipped lubricant-feed wheel. The feed wheel is located beneath the supply cannister. Each scoop of the feed wheel is filled with powder as it passes the cannister and is emptied after 180 degrees of wheel travel by a carrier-gas jet. The lubricator is shown in Figure 7.

The original lubricator has a capacity large enough to insure 2-1/2 hours of continuous gear rig testing without refilling. However, since the temperature-cycle tests required a minimum of 3 hours of operation, it was necessary to expand the capacity of the lubricator. The modification was accomplished by removing the housing and cover of the original lubricator and securing a hollow cylinder 16-inches long on the existing base. A frame was installed to support the agitator. The lubricator was then recalibrated to determine what the effect of the additional lubricant weight would be--that is, would it compact the lubricant or change the lubricant delivery rate.

This modification provided the following advantages:

1. Lubricant capacity was doubled (5 hour minimum lubricant capacity).

2. More lubricant could be added without disassembling lubricator.

3. Visual inspection could be made to observe level of lubricant.

The test rig was adapted for application of powder lubrication in the test-gear chamber. The lubricant was fed to the gears through a tube which was directed downward toward the meshing point of the gears as shown in Figures 3, 4, 5 and 8. Prior to accepting the present lubricant feed tube arrangement, tests were made on a longitudinal feed tube as shown in Figure 9. This technique was discarded because it did not provide an adequate supply of lubricant to the far sides of the tooth surfaces.

VARIABLE SPEED MOTOR DRIVE

Following test G-123 it was decided to modify the test rig to eliminate the severity of the impact load placed on the gears by initial acceleration of the 5-hp gear rig motor. It was believed that impact loads were not one of the controlled variables and therefore should be minimized. This was accomplished by installing a large three-gang Variac control in series with the three-phase test rig motor. This enabled the operator to increase the test-rig motor speed gradually which minimized impact loads on the test gears.

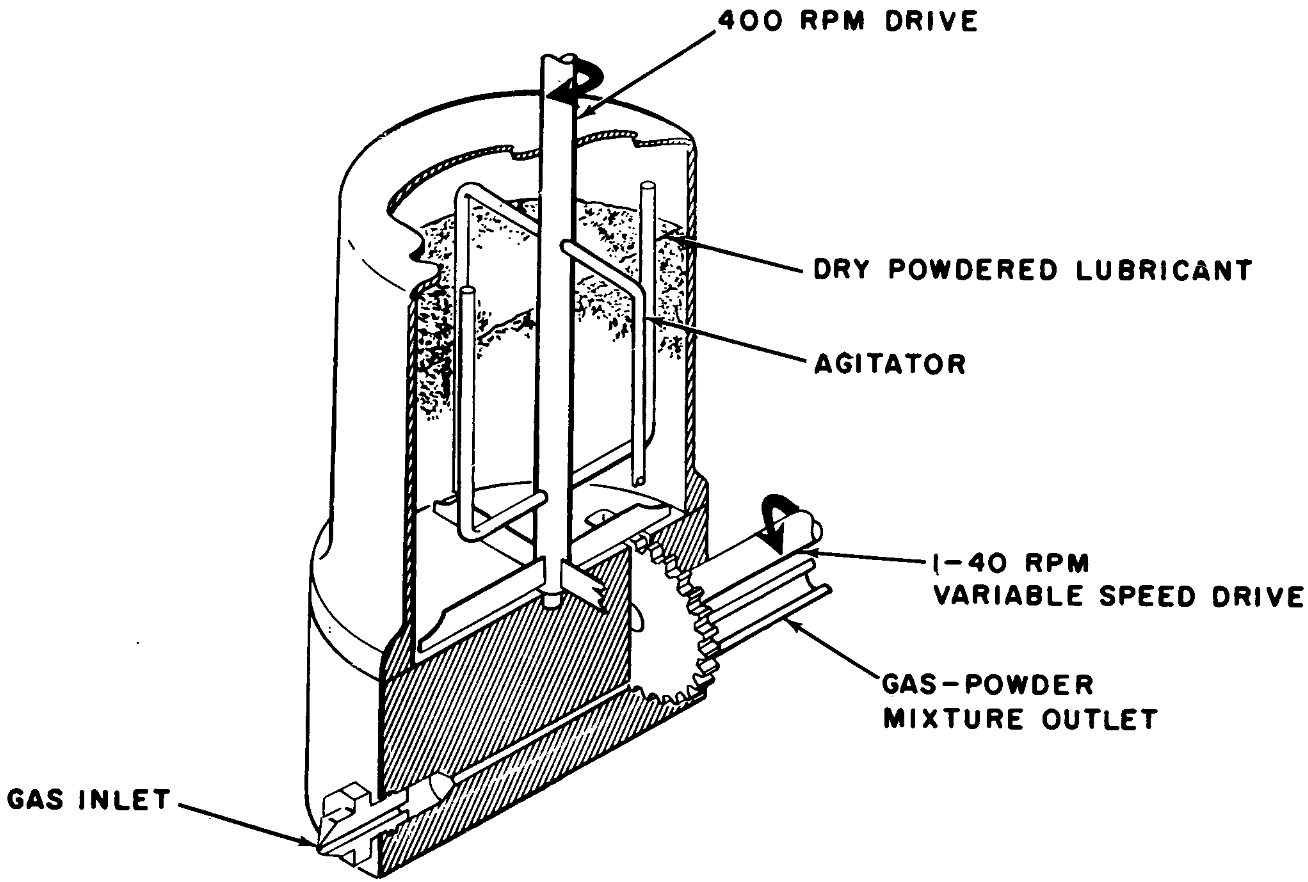


Figure 7. Variable-Speed Gear-Feed Lubricator

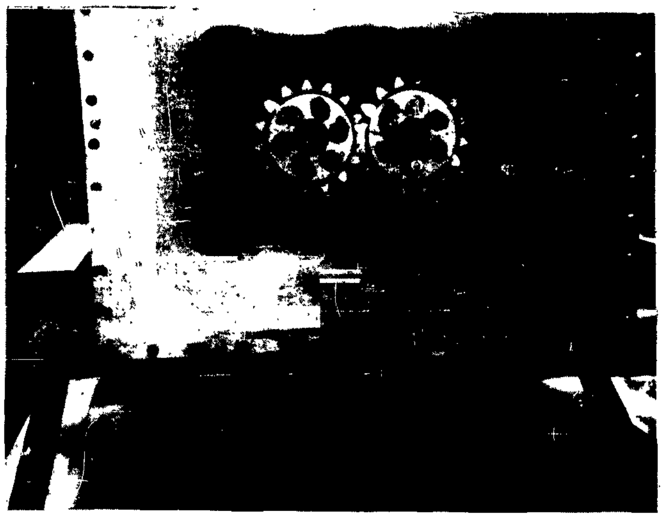


Figure 8. Unshielded Lubricant Feed Tube Installed in Test Head

Figure 9. Longitudinal Lubricant Feed Assembled to Test Rig

SECTION 3
TEST PROCEDURE

METHOD OF CONDUCTING TESTS

The following test procedure was established early in the program. Similar procedures were used throughout the gear-test program.

1. Test gears measured and inspected.
2. Pulleys and timing belt adjusted to obtain proper speed.
3. Test gears installed in test rig.
4. Shields installed in test rig.
5. Endplate installed on test head.
6. Test-rig oil pumps turned on.
7. Test gears loaded.
8. Lubricator started and carrier-gas flow control opened.
9. Test gears manually rotated.
10. Test-rig drive motor turned on.
11. Following 15 minutes of operation, test rig turned off.
12. Lubricator turned off and carrier-gas flow control closed.
13. Test-gear load checked. (Resumption of test depends on reaction to step 15.
14. Endplate and shields removed.
15. Test gears visually inspected for satisfactory surface condition.
16. If test is to be resumed, shields and endplate are reinstalled.
17. Steps 8 through 13 repeated three times. (Resumption of test depends on reaction to step 13.)
18. Test run completed. Steps 14 and 15 repeated. Test rig completely shut down. Test gears removed from test rig.
19. Wear data and other observations recorded. Investigations of wear and other unusual or unsuspected test-gear conditions initiated.

INSPECTION METHODS

To measure the gear wear of the five diametral pitch gears measurements were taken using 0.4000-inch diameter pins. Starting with test G-108, two additional measuring-pin sizes were used having diameters of 0.3125 and 0.7406 inch. The 0.3125-inch pins indicated dedendum wear, the 0.4000 inch pins indicated wear in the area of the pitch diameter, and addendum wear was indicated with the 0.7406 inch pins.

The 12/14 pitch gear-wear measurements were taken with 0.144-inch and 0.210-inch diameter pins. Pitch-diameter wear was indicated by the 0.144-inch pins while tip-diameter

wear was indicated by the 0.210-inch pins. Table 1 lists a set of typical gear-wear measurements. Since there are 39 teeth, 40 measurements are required as indicated. This particular test gear was used in Test G-121 and failed after 15 hours and 10 minutes of operation. The test gear exhibited its greatest wear during the first five hours of operation when it was at room temperature and the lubricant did not begin to adhere to the gear teeth. The next 10 hours of operation were at 900° F and the 0.210 diameter pin measurements indicate that the gear teeth have almost returned to their original dimensions due to the buildup of the lubricant. It should be noted that measurements No. 33 through No. 36 are distorted due to impressions made by the gear puller. However, these gear teeth were reconditioned prior to continuation of the test.

Visual inspection was employed to determine the condition of the test gears and the condition and distribution of the lubricant film on the gear surfaces.

During operation, gear-vicinity temperatures were recorded and reported as ranges or cycle limits of temperature measurements. Actual gear-tooth temperature was read only when the test rig was stopped, usually at intervals of 1 hour, by moving the thermocouple into contact with the gear teeth. Experience indicated that actual gear-tooth temperature was plus or minus 15° F of the gear-tooth vicinity temperature.

The average lubricant flow rate from the lubricator per test interval was derived by checking the lubricator weight before the test interval and again following the test interval. The average lubricant flow rate was the difference in the weights divided by the elapsed time of the test run.

Gear-test data were logged at 10-minute intervals during test operation on log sheets as shown in Figure 10.

TABLE 1. GEAR TOOTH MEASUREMENTS - HAYNES NO. 151 GEAR TEST G-121

	0.144 DIAMETER PIN MEASUREMENTS (PITCH DIAMETER)					0.210 DIAMETER PIN MEASUREMENTS (ADDENDUM)				
Reading Number	Initial Reading	Final Reading (14 Hrs)	Total Change In. x 10^{-4}	Change After 9 Hours In. x 10^{-4}	Change After 5 Hours In. x 10^{-4}	Initial Reading	Final Reading (14 Hrs)	Total Change In. x 10^{-4}	Change After 9 Hours In. x 10^{-4}	Change After 5 Hours In. x 10^{-4}
1	3.4203	3.4200	- 3	-13	- 6	3.6449	3.6450	+ 1	- 1	- 4
2	3.4208	3.4199	- 9	-18	-13	3.6450	3.6450	0	- 1	- 8
3	3.4203	3.4200	- 3	-13	- 8	3.6450	3.6450	0	- 2	- 5
4	3.4204	3.4200	- 4	-14	-10	3.6450	3.6450	0	- 5	- 8
5	3.4202	3.4201	- 1	-12	-10	3.6450	3.6450	0	- 2	- 1
6	3.4204	3.4200	- 4	-14	-14	3.6450	3.6449	- 1	- 2	- 7
7	3.4200	3.4200	0	-10	- 8	3.6450	3.6449	- 1	- 5	- 5
8	3.4205	3.4200	- 5	-15	-15	3.6450	3.6450	0	- 4	- 4
9	3.4200	3.4200	0	-10	- 7	3.6450	3.6450	0	- 2	- 2
10	3.4206	3.4200	- 6	-16	-14	3.6450	3.6450	0	- 3	- 3
11	3.4209	3.4200	- 9	-19	-17	3.6450	3.6451	+ 1	- 5	- 6
12	3.4210	3.4200	-10	-20	-17	3.6450	3.6450	0	- 9	- 2
13	3.4209	3.4200	- 9	-18	-15	3.6450	3.6450	0	- 1	- 3
14	3.4205	3.4200	- 5	-15	-13	3.6450	3.6450	0	- 2	- 4
15	3.4203	3.4200	- 3	-13	-12	3.6450	3.6450	0	- 2	- 4
16	3.4210	3.4200	-10	-20	-19	3.6450	3.6449	- 1	- 1	- 2
17	3.4209	3.4200	- 9	-19	-17	3.6449	3.6450	+ 1	- 1	0
18	3.4205	3.4200	- 5	-15	-14	3.6449	3.6450	+ 1	- 3	- 1
19	3.4209	3.4200	- 9	-19	-18	3.6450	3.6450	0	+ 6	- 3
20	3.4208	3.4200	- 8	-18	-17	3.6450	3.6450	0	- 2	- 3
21	3.4206	3.4200	- 6	-16	-15	3.6450	3.6450	0	- 5	- 3
22	3.4205	3.4200	- 5	-15	-15	3.6450	3.6450	0	- 5	- 5
23	3.4205	3.4200	- 5	-15	-14	3.6450	3.6450	0	- 2	- 5
24	3.4209	3.4200	- 9	-15	-18	3.6449	3.6450	+ 1	- 1	- 3
25	3.4205	3.4200	- 5	-15	-13	3.6448	3.6450	+ 2	- 1	- 6
26	3.4209	3.4200	- 9	-15	-18	3.6450	3.6450	0	- 5	- 5
27	3.4210	3.4200	-10	-20	-19	3.6450	3.6450	0	0	- 4
28	3.4210	3.4200	-10	-19	-20	3.6450	3.6450	0	- 2	- 6
29	3.4210	3.4200	-10	-19	-18	3.6450	3.6450	0	0	- 2
30	3.4210	3.4200	-10	-19	-18	3.6450	3.6450	0	- 2	- 3
31	3.4210	3.4200	-10	-19	-18	3.6450	3.6450	0	- 2	- 5
32	3.4211	3.4200	-11	-22	-19	3.6450	3.6450	0	- 5	- 3
33	3.4211	3.4200	-11	-22	-21	3.6458	3.6449	- 9	-10	- 8
34	3.4211	3.4200	-11	-19	-19	3.6462	3.6448	-14	-11	-11
35	3.4211	3.4200	-11	-19	-18	3.6462	3.6450	-12	-10	-12
36	3.4210	3.4200	-10	-20	-17	3.6450	3.6465	+15	- 5	0
37	3.4210	3.4200	-10	-20	-17	3.6450	3.6452	+ 2	- 5	- 2
38	3.4210	3.4200	-10	-18	-15	3.6450	3.6450	0	- 6	- 1
39	3.4202	3.4200	- 2	-11	-12	3.6450	3.6450	0	- 6	- 7
40	3.4202	3.4200	- 2	-12	-12	3.6450	3.6450	0	- 3	- 3

TEST No. ______ GEAR TEST DATA SHEET SHEET ___ OF ___

GEAR MATERIAL :- ______________________________

LUBRICANT ______________________________ CARRIER GAS ________

DATE & TIME	DRIVE MOTOR AMPS.	TEST GEAR BOX TEMP, °F		TEMP, °F		RIG OIL TEMP, °F		OIL TANK TEMP, °F	CARRIER GAS		RIG OIL IN PRESS, PSIG		POWERSTAT %		LUBE MOTOR		Total Running Time Min.	Cycle Time Min.
		L.G. ①	R.G. ②	GEAR TEETH ③	LUBE OUT ④	L ⑤	R ⑥	⑦/⑧	PRESS, PSIG	FLOW, %	FRONT	REAR	GEAR BOX Ⓐ	GEAR BOX Ⓑ	DRIVE PRESS PSIG	CPS		

Figure 10. Gear Data Log Sheet

SECTION 4
TEST GEARS

PHASE I GEARS

Typical 15-tooth and 16-tooth coarse pitch test gears, defined as Phase I gears, are shown in Figures 11 and 12. The gears have the following characteristics:

Pressure Angle (1) . . . . 20°

Diametral Pitch 5

Hunting-Tooth Arrangement . . . . 15-tooth gear meshes with 16-tooth gear

Gear Materials	Tooth-Face Width	Hardness (R_C)
SAE 9310 Steel	1/4 in.	59
B.S. EN 34 Steel	3/16 in.	62-65
M-2 Tool Steel	1/4 in.	57
M-50 Tool Steel	1/4 in.	60

Sliding Velocity (2) . . . . 5550 fpm

Contact Stress (max) (3) . . . . 129, 000 psi

(1) Actual contact pressure angle 26 degrees, 19 minutes due to extended gear centers.

(2) Tip measurement at speed of 15, 000 rpm.

(3) Calculated with load of 1000 ppi(tf)* applied.

Characteristics of Phase I gear materials B. S. EN 34 is a 2 percent nickel-molybdenum steel. The British-made gears that were used were carburized to R_C 62-65 case hardness.

SAE 9310 steel gears were case hardened to a minimum of R_C59 by carburizing.

*The abbreviation ppi(tf) is defined as the load applied to each test gear in terms of pounds per linear inch of tooth-face width.

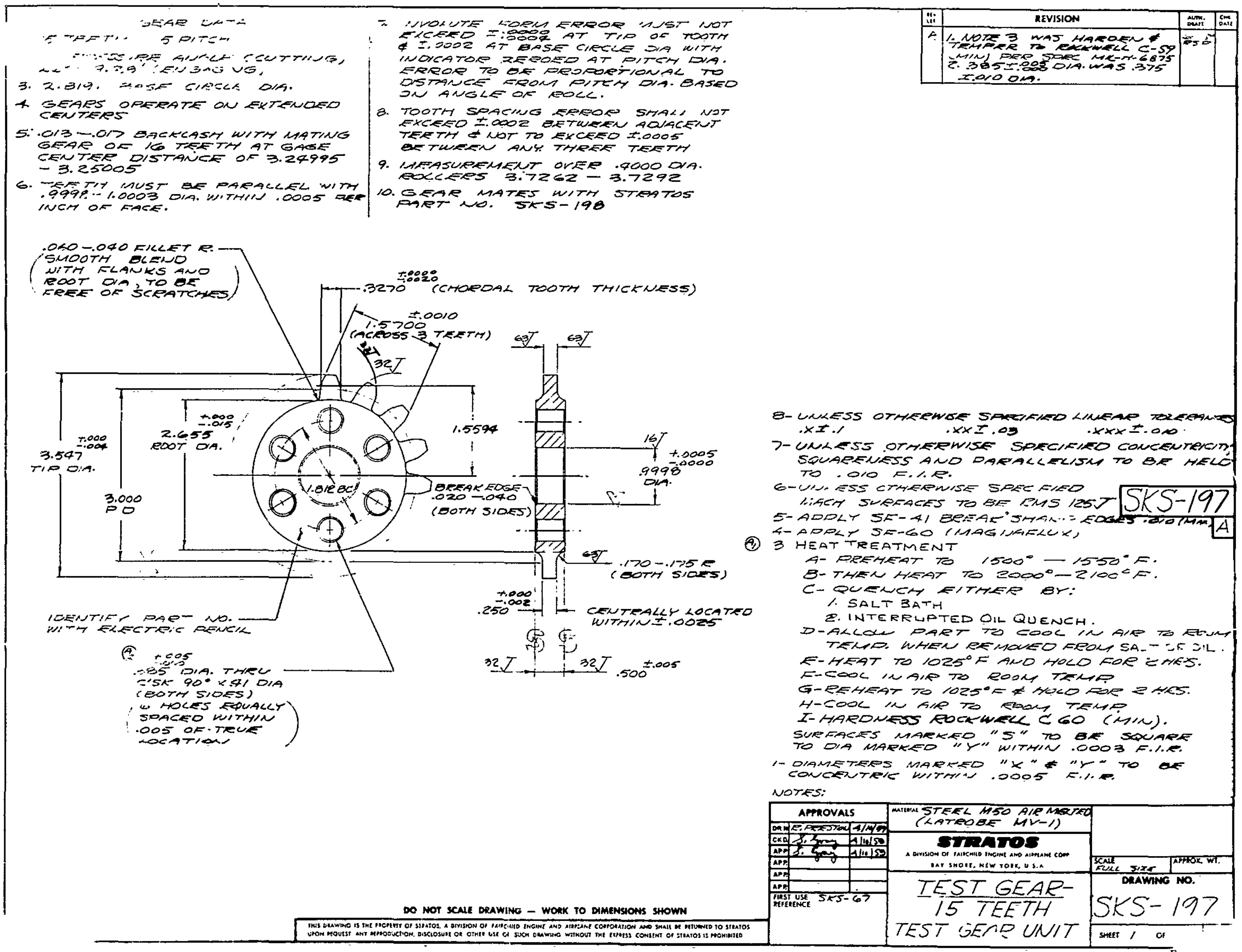


Figure 11. M-50 Tool Steel Gear With 15 Teeth Used in Phase I Evaluations

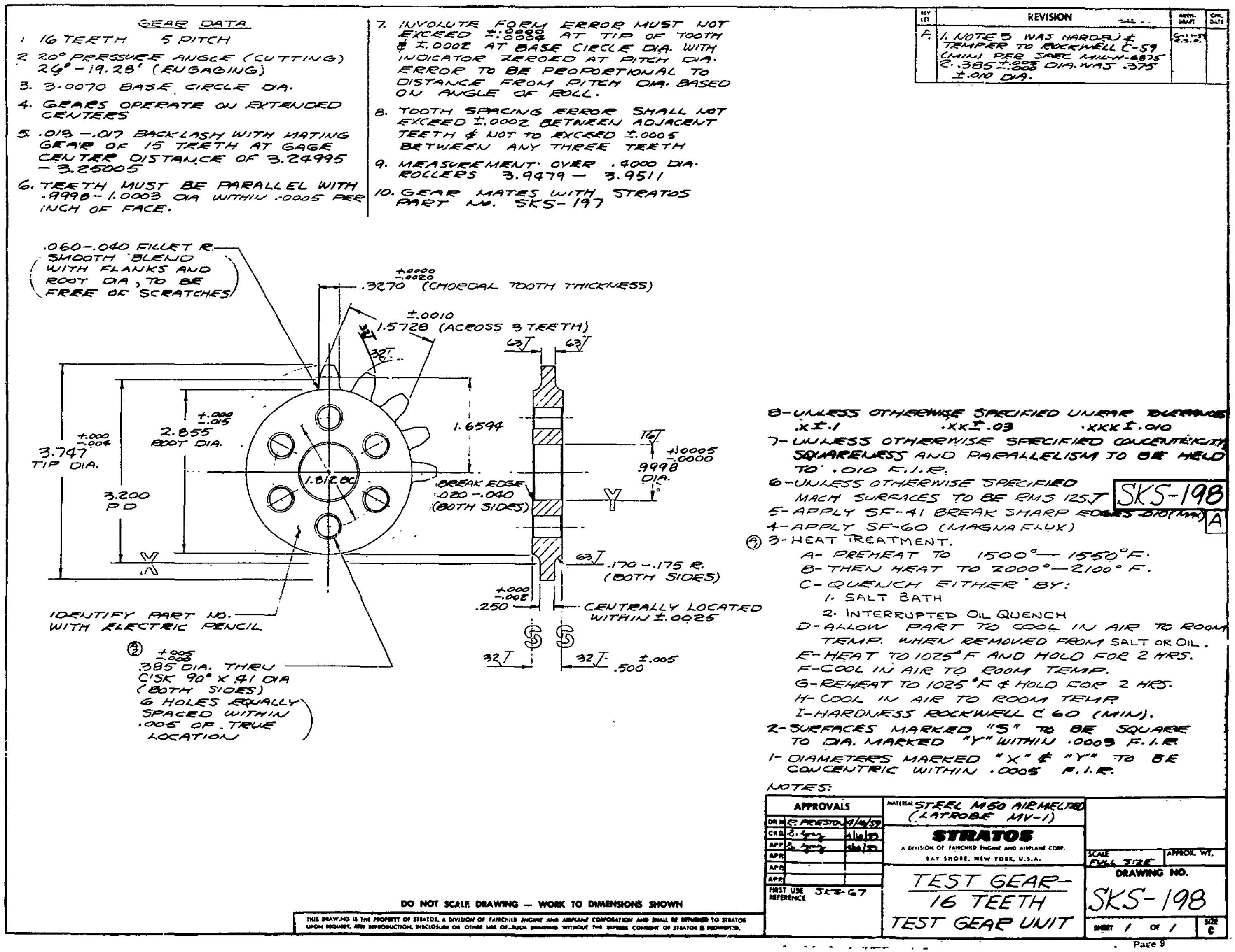


Figure 12. M-50 Tool Steel Gear With 16 Teeth (5 Diametral Pitch)

PHASE II GEARS

The gears used in the Phase II investigations were designed to operate at the high temperatures. They were cast from nickel-base and cobalt-base superalloys and 39 spur-type teeth are machined in each gear. They possess the following characteristics:

Pressure Angle		20°
Diametral Pitch		12/14 stub
Hunting-Tooth Arrangement (1)		None
Tooth-Face Width		1/4 in.
Gear Materials		Hardness (R_C)
Nickel-base Superalloy	Rene' 41	30
Cobalt-base Superalloy	Haynes Alloy No. 151	33
Cobalt-base Tool Alloy	Haynes Stellite Alloy No. 6B	39
Sliding Velocity (2)		2875 fpm
Contact Stress (max) (3)		123,000 psi

(1) Gear having 39 teeth meshes with 39-tooth gear.
(2) Tip measurement at speed of 15,000 rpm.
(3) Calculated with load of 1000 ppi (tf)* applied.

Characteristics of Phase II Gear Materials

Rene' 41 is a nickel-base superalloy steel that exhibits excellent high-temperature properties, particularly yield and fatigue resistance.

Haynes Stellite No. 151 is a cobalt-base superalloy steel. Its high-temperature properties include dimensional stability and high hardness qualities.

Haynes Stellite No. 6B is a wrought cobalt-chromium-tungsten tool alloy that was selected as gear material for this program because of its high hot hardness qualities. Since it is a wrought material, it provides more toughness and shock resistance than cast materials. This alloy exhibited superior wear resistance and showed most resistance to plastic flow in rolling-contact disk experiments conducted by Battelle Memorial Institute, Columbus, Ohio (Reference 1). Figure 13 is a typical fine-pitch gear used in Phase II evaluations.

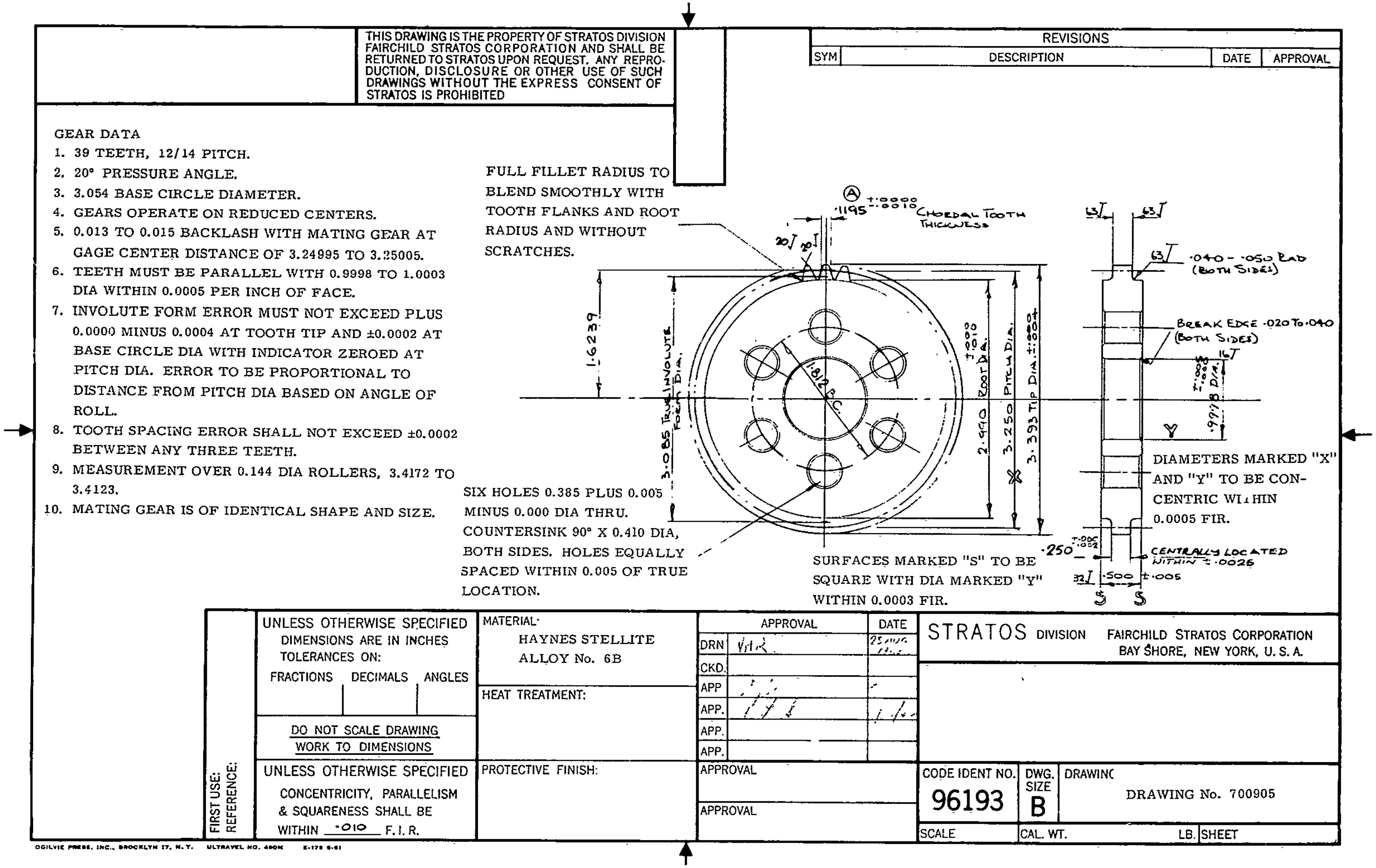


Figure 13. Haynes Stellite Alloy No. 6B Test Gear With 39 Teeth in Phase II Evaluations

SECTION 5
LUBRICATION

CHARACTERISTICS AND CHOICE OF POWDER LUBRICANTS

The two powder lubricant mixtures selected for high-temperature tests conducted during this program were:

1. Micronized Acheson No. 38 graphite (83-1/3 percent) plus cadmium oxide (16-2/3 percent) in air carrier.

2. Molybdenum disulfide (76 percent) plus metal-free phthalocyanine (24 percent) in nitrogen carrier.

Both lubricants had successfully lubricated angular contact ball bearings in the high-temperature rolling contact bearing program conducted under Contract AF33(616)-6589. The graphite plus cadmium oxide mixture was suitable in the range from room temperature to 1000° F, while the molybdenum disulfide plus metal-free phthalocyanine mixture demonstrated a satisfactory operating range from room temperature to 1200° F. The study of powder lubricants that resulted in the choices made for this program is reported in Reference 3.

Emphasis was placed on the graphite-plus-cadmium-oxide lubricant during this program since it is effective in an air environment. The molybdenum-disulfide-plus-phthalocyanine lubricant requires an inert environment to prevent oxidation of MoS_2 at temperatures in excess of approximately 800° F (Reference 2).

SECTION 6
DISCUSSION OF TEST RESULTS

PHASE I TESTS

Checkout and Calibration - Ambient Temperature Tests

The initial gear tests, G-100 through G-106, were devised to evaluate the operating characteristics of the test apparatus at ambient temperature. Since many of the tests during the initial period did not result in gear failure, as in later tests, the gears were able to be reversed for further testing.

Such tests were designated with a letter being added to the test number, for example: G-100A. Loads ranging from 440 to 960 ppi(tf) were imposed on the test gears. In the beginning, the gears were operated at a speed of 5300 rpm, but this was increased in later tests during the period to 4700 rpm, and the final 10-minute run in test G-106 was at 10, 350 rpm. This test was stopped due to a high noise level and an indication or rising temperature in the vicinity of the powder lubricant discharge jet. Inspection indicated that the gear-tooth temperature had reached approximately 700° F. Flanks were worn and scored. Grooves were in the pitch diameters of the gears. Except for test G-100, in which lubricating oil per Military Specification MIL-L-7808 was used as the test-gear lubricant, a proven powder lubricant, molybdenum disulfide (MoS_2), in an air carrier was applied to the gears. An air carrier was used since oxidation of the MoS_2 would not occur at ambient temperatures.

The ambient temperature tests continued in the second series with efforts to reduce gear wear by varying flow of the powder lubricant and by honing the gear teeth prior to testing. The high temperature lubricant, graphite plus CdO, was used for all tests commencing with G-106A. Gears fabricated from the case-hardened steels were used for all tests through G-107A. Tests G-108 and G-108A were evaluations of a set of M-50 tool alloy steel gears in which it was determined that honing was unnecessary since grind marks from the manufacturing of the gears was evident following 4 hours of testing. Phase I ambient temperature evaluations (G-100 through G-108A) are tabulated in Table 2.

High Temperature Tests

Phase I gears were subjected to high temperature tests to evaluate the gear materials and gear design as well as check out the test rig for high temperature operation. Phase I gear materials are suitable to operate at 1000° F maximum temperature and the data obtained from these tests were used to optimize the gear design and contributed to establish compatible test procedures.

Elevated temperature evaluations began with test G-109. Temperature was maintained at approximately 800° F for the first 4 hours of the test but increased to about 1000° F during the final 8 minutes. The test was stopped due to indications of high rig drive power requirement, high noise level, and high tooth-vicinity temperature. Wear measurements over pins were taken frequently during this test. Negligible wear was indicated. Inspection of the gears at the conclusion of the test revealed that the contact surfaces were in poor condition and that backlash was lost.

TABLE 2. PHASE I AMBIENT TEMPERATURE EVALUATIONS

Test No.	Objective of Test	Gear Material	Lubricant and Carrier	Load in lb/in. (tf) (1)	Speed (rpm)	Wear Measurement (2) 15-Tooth Gear Before	15-Tooth Gear After	16-Tooth Gear Before	16-Tooth Gear After	Time Interval (hrs:min)	Lubricant Flow Rate (gm/min)	Remarks
G-100	Confirm rig operation.	B.S.EN 34 (case hardened)	MIL-L-7808	589 960	5300 5300	Not taken Not taken		Not taken Not taken		0:14 0:17	-- --	Gears had polished wear surfaces. No surface damage noted. Operation smooth. Total test time: 31 min.
G-100A	First powder run to determine flow patterns, effect of powder, and for rig familiarization.	B.S.EN 34 (same faces as G-100)	MoS_2 in air	589 960	5300 5300	Not taken Not taken		Not taken Not taken		0:20 0:40	-- --	Heavy scoring of teeth suffered although no significant change in drive power indicated. Meager quantity of lubricant deposited on teeth. Appears that gears should be shielded to confine power to meshing point. Additional 60-min test time applied on these faces. Grooves in teeth at pitch diameter of gears.
G-100B	Effects of Shield No. 1 and honing of gear flanks.	B.S.EN 34 (case hardened)	MoS_2 in air	589 960	5300 5300	Not taken Not taken		Not taken Not taken		0:20 0:40	-- --	Gear flanks honed to remove grinding marks. Gears slightly noisy at start of test. Slight scoring of teeth. Slight lubricant buildup on flanks. Grooves in teeth at pitch diameter of gears.
G-101	Effects of shields No. 1 and No. 2 and honing of gear flanks.	B.S.EN 34 (case hardened)	MoS_2 in air	589 960	5300 5300	Not taken Not taken		Not taken Not taken		0:20 0:40	-- --	Gear flanks honed to remove grinding marks. Uneven lubricant film on flanks, some scoring on tips of teeth, and pitch diameter wear. Grooves in teeth at pitch diameter of gears.
G-101A	Confirm G-101.	B.S.EN 34 (case hardened) Opposite faces of test gears G-101.	MoS_2 in air	589	5300	Not taken		Not taken		0:15	--	Gear flanks honed to remove grinding marks. Drive power increased sharply at 8 minutes and then decreased. Test stopped at 15 minutes due to increased drive power requirement and lubricant outlet temperature. Blue-purple gear teeth indicated tooth temperature of approximately 700°F. Heavy scoring of tooth flanks. Opposite flanks of teeth may have made contact (loss of backlash).
G-102	Effects of shields No. 1 and No. 2 with gears of SAE 9310 material.	SAE 9310 (case hardened)	MoS_2 in air	440 440	5300 5300	3.7283 3.7280	3.7280 3.7270	3.9506 3.9503	3.9503 3.9495	1:00 0:24	0.38	Excessive amount of oil found in test chamber after first 60 min. Teeth highly polished and coated with lubricant film. Test restarted under same load and speed conditions since oil could have affected results of first 60-min run. Noise started after 9 min. After 24-min run, high noise level and high lubricant outlet temperature caused shutdown. Slight tan coloration of teeth indicated approximate temperature of 400°F. Tooth flanks scored and edges burred showing excessive wear. Total test time: 84 minutes. Grooves on teeth at pitch diameter of gears.

TABLE 2. PHASE I AMBIENT TEMPERATURE EVALUATIONS (Cont)

Test No.	Objective of Test	Gear Material	Lubricant and Carrier	Load in lb/in. (tf) (1)	Speed (rpm)	Wear Measurement (2) 15-Tooth Gear Before	15-Tooth Gear After	16-Tooth Gear Before	16-Tooth Gear After	Time Interval (hrs:min)	Lubricant Flow Rate (gm/min)	Remarks
G-102A	Effects of shields No. 1 and No. 2 with gears of SAE 9310 material and higher lubricant flow rate.	SAE 9310 (case hardened) Opposite faces of test gears G-102.	MoS_2 in air	720	5300	3.7270	3.7256	3.9495	3.9436	1:00	0.38	Gear noise level increased after 28 min together with drive power. High noise level continued during test while adjusting for various combinations of lubricant flow and carrier-gas pressure. Wear surfaces in good condition at 15-min inspection. At conclusion of test, teeth had blue-purple coloration indicating they had reached temperatures of approximately 700°F. Heavy scoring evident and edges burred. Grooves in teeth at pitch diameter of gears.
G-103	Effect of longitudinal lubricant feed.	SAE 9310 (case hardened)	MoS_2 in air	440	5300	3.7286	3.7284	3.9507	3.9502	0:04	--	Test stopped due to increase in drive power requirement. Teeth in poor condition. Apparently insufficient lubricant flow to far side of each tooth. Grooves in teeth at pitch diameter of gears.
G-103A	Effects of various shields.	SAE 9310 (case hardened) Opposite faces of test gears G-103.	MoS_2 in air	440	5300	3.7284		3.9502		0:10	--	First 10-minute run with No. 1 shield at increased lubricant flow. Inspection showed no improvement in tooth condition.
							3.7284		3.9501	0:50	--	Shields No. 1 and No. 3 used; high lubricant flow set. Inspection showed teeth in excellent condition.
				720	5300	3.7284	3.7284	3.9501	3.9501	1:00	--	Shields No. 1 and No. 3 used together with same lubricant flow as during previous 50 min. Contact surfaces in excellent condition well coated with film of lubricant. No measurable wear noted.
				1000	5300	3.7284	3.7279	3.9501	3.9496	1:00	--	Shields No. 1 and No. 3 used together with same lubricant flow as during previous hour. Quiet and smooth operation for initial 45 min; final 15-min operation at increased noise level, drive power, and lubricant outlet temperature. Gears reached approximately 700°F; were scored and burred. Grooves in teeth at pitch diameter of gears. Total test time: 3 hr.
G-104	Confirm 720 lb/in. (tf) successful run in G-103A and extend to higher speeds.	SAE 9310 (case hardened)	MoS_2 in air	720	5300	3.7285	3.7285	3.9502	3.9502	1:00	--	Shields No. 1 and No. 3 used together with same lubricant flow as during final 2 hours 50 minutes of test G-103A. Teeth in fair condition showing slight tan coloration.
				720	7400	3.7285	3.7277	3.9502	3.9494	0:20	--	Shields No. 1 and No. 3 used together with same lubricant flow as during previous hour. Noise and lubricant outlet temperature increased after 14 min. Teeth reached temperature of approximately 700°F; were scored and burred. Grooves in teeth at pitch lines. Total test time: 1 hr 20 min.

TABLE 2. PHASE I AMBIENT TEMPERATURE EVALUATIONS (Cont)

Test No.	Objective of Test	Gear Material	Lubricant and Carrier	Load in lb/in. (tf) (1)	Speed (rpm)	Wear Measurement (2) 15-Tooth Gear Before	15-Tooth Gear After	16-Tooth Gear Before	16-Tooth Gear After	Time Interval (hrs:min)	Lubricant Flow Rate (gm/min)	Remarks
G-104A	Effect of using shields No. 1, No. 3 and No. 4	SAE 9310 (case hardened) Opposite faces of G-104.	MoS_2 in air	440	7400	3.7277	3.7277	3.9494	3.9495	1:00	--	First test using shield No. 4. Same lubricant flow rate set as in test G-104. Gear-tooth contact surfaces in excellent condition. Original grinding marks on teeth still visible.
				720	7400	3.7277	3.7263	3.9495	3.9498	1:00	--	Drive-power fluctations during first 10 minutes of operation but a minimum of noise. Noise level increased after 10 minutes. Contact surfaces scored and overheated. Grooves in teeth at pitch diameter of both gears.
G-105	Confirm second hour of test G-104A.	SAE 9310 (case hardened)	MoS_2 in air	720	7400	3.7290	3.7268	3.9504	3.9476	0:09	--	Drive-power fluctuations and high noise level caused termination of test. Teeth worn and scored, with burred edges and coloration indicating temperature of 700°F. Grooves in teeth at pitch lines. Shields No. 1, No. 3 and No. 4 used.
G-105A	Investigate loads between 440 and 720 lb/in. (tf) and determine minimum lubricant flow rate of MoS_2 required. Shields No. 1, No. 3 and No. 4 used.	SAE 9310 (case hardened) Opposite faces of G-105.	MoS_2 in air	440	7400	3.7268		3.9476		1:00	--	Shields No. 1, No. 3 and No. 4 used. Contact surfaces in good condition.
				562	7400		3.7273		3.9480	2:02	--	Test to determine minimum amount of lubricant flow required. Lubricant flow rates decreased at 10-min intervals. Rate measured according to number of teeth of lubricant feed wheel passing carrier gas jet per min. Test began at 34 scoops per min. Lubricator motor pressure decreased to rate of 20 scoops per min. at which flow noise level and lubricant-outlet temperature increased. Contact surfaces slightly abraded. Line on teeth at pitch diameter of gears.
G-106	Extend speed to 10, 350 rpm; shields No. 1, No. 3 and No. 4 used.	SAE 9310 (case hardened)	MoS_2 in air	440	7400	3.7281		3.9508		0:10	--	Short break-in run. Tooth contact surfaces in excellent condition.
				440	10, 350		3.7270		3.9502	0:10	--	Test terminated due to high noise level and lubricant outlet temperature. Increasing lubricant flow rate did not influence noise level, but decreasing flow rate decreased noise level. Teeth overheated to temperature of approximately 700°F. Teeth worn with scored faces. Grooves in teeth at pitch diameters of each gear.

NOTES
(1) Pounds per linear inch of tooth face.
(2) 0.400 in. dia. measuring pins used to measure gear-tooth wear.

TABLE 2. PHASE I AMBIENT TEMPERATURE EVALUATIONS (Cont)

Test No.	Objective of Test	Gear Material	Lubricant and Carrier	Load in lb/in. (tf) (1)	Speed (rpm)	Wear Measurement (2) 15-Tooth Gear Before	15-Tooth Gear After	16-Tooth Gear Before	16-Tooth Gear After	Time Interval (hr:min)	Lubricant Flow Rate (gm/min)	Remarks
G-106A	Effects of Shields No. 1, No. 3 and No. 4 used with SAE 9310 gears and graphite plus CdO lubricant.	SAE 9310 (case hardened) Opposite faces of G-106	5 parts micronized Acheson No. 38 graphite plus 1 part CdO in air	440	5300	3.7270	3.7275	3.9502	3.9502	0:15	--	Uneven lubricant film on gear flanks. Abrasion of addendum of 15-tooth and dedendum of 16-tooth gears. No measurable wear. Line across pitch diameter of gears.
G-107	Effects of Shields No.1, No. 3 and No. 4 using higher lubricant flow rates with SAE 9310 gears and graphite plus CdO lubricant.	SAE 9310 (case hardened)	5 parts micronized Acheson No. 38 graphite plus 1 part CdO in air	440	5300	3.7287	3.7288	3.9506	3.9502	1:00	1.95	During first 45 minutes, gears ran well with intermittent noise at low-noise level. During final 15 minutes, noise level was low and steady. Lubricant outlet temperature started to increase during last 5 minutes of test. Some abrasion of addendum of 15-tooth and dedendum of 16-tooth gears. Line at pitch diameter. Surface appeared worn, but measurements do not indicate wear.
G-107A	Same as G-107 (tooth flanks honed) and to study effects of decreasing lubricant flow rate.	SAE 9310 (case hardened) Opposite faces of G-107.	5 parts micronized Acheson No. 38 graphite plus 1 part CdO in air	440	5300	3.7288		3.9502		1:00	--	Gears in good condition at the end of 1-hour run. Lubricant flow decreased in steps from 32 scoops to 26 scoops per minute. Line at pitch diameter.
				562	5300					1:00	--	Gears in good condition at the end of 1-hour run. Lubricant flow decreased in steps from 26 scoops per minute to 20 scoops per minute. Line at pitch diameter.
				720	5300					1:00	--	Gears in good condition at the end of 1-hour run. Lubricant flow decreased from 20 scoops per minute to 19 teeth per minute. Line at pitch diameter.
				1000	5300		3.7283		3.9504	0:12	--	Slight power increase (6.6 to 6.8 amp) and slow increase of lubricant outlet temperature (206°F to 240°F). Increase in noise level noted. Gear temperatures reached approximately 700°F. Line at pitch diameter. The teeth were scored and burred with some lubricant film buildup. Lubricant flow rate equalled 18 scoops per minute.
G-108	Effects of Shields No. 1, No. 3 and No. 4 with tool steel gears and graphite plus CdO lubricant. (Tooth flanks honed.)	M-50 tool steel heat treated to R_c 60 min.	5 parts micronized Acheson No. 38 graphite plus 1 part CdO in air	440	5300	3.4686(2a) 3.7289 4.6126(2b)		3.6865(2a) 3.9502 4.8449(2b)		1:00	--	Gears in good condition at end of 1 hour. Lubricant flow rate equalled 18 scoops per minute.
				562	5300					1:00	--	Gears in good condition at end of 1 hour. Lubricant flow rate equalled 19 scoops per minute.

TABLE 2. PHASE I AMBIENT TEMPERATURE EVALUATIONS (Cont)

Test No.	Objective of Test	Gear Material	Lubricant and Carrier	Load in lb/in. (tf) (1)	Speed (rpm)	Wear Measurements (2) 15-Tooth Gear Before	15-Tooth Gear After	16-Tooth Gear Before	16-Tooth Gear After	Time Interval (hr:min)	Lubricant Flow Rate (gm/min)	Remarks
G-108 (cont)				720	5300					1:00	--	Gears in good condition at end of 1 hour. Lubricant flow rate requalled 19 scoops per minute.
				1000	5300					1:00	--	Gears in good condition at end of 1 hour. Lubricant flow rate equalled 21 scoops per minute.
				440	7400					0:15	--	Gears in good condition at end of 15 minutes. Lubricant flow rate equalled 21 scoops per minute.
				562	7400					0:45	--	Gears in good condition at end of 45 minutes. Lubricant flow rate equalled 21 scoops per minute.
				720	7400					1:00	--	Gears in good condition at end of 1 hour. Lubricant flow rate equalled 21 scoops per minute.
				1000	7400		3.4682(2a) 3.7291 4.6125(2b)		3.6861(2a) 3.9502 4.8448(2b)	1:00	--	Gears in good condition after total of 7 hours of testing. Film of lubricant on addenda, but little or none at dedenda. Slight line at pitch diameter.
G-108A	Same as test G-108, but teeth not honed.	M-50 tool steel (heat treated to R_c 60 min.) Opposite faces of G-108	5 parts of micronized Acheson No. 38 graphite plus 1 part of CdO in air	440	7400	3.4682(2a) 3.7291 4.6125(2b)		3.6861(2a) 3.9502 4.8448(2b)		1:00	--	Gears in good condition at the end of 1 hour. Good lubricant film on teeth. Grinding marks still evident. Line across teeth at pitch diameter. Lubricant flow rate equalled 19 scoops per minute.
				562	7400					1:00	--	Visual inspection showed same conditions as after previous hour. Lubricant flow rate equalled 19 scoops per minute.
				720	7400					1:00	--	Visual inspection showed same conditions as after previous hour. Lubricant flow rate equalled 19 scoops per minute.
				1000	7400		3.4679(2a) 3.7285 4.6125(2b)		3.6860(2a) 3.9499 4.8446(2b)	1:00	--	Gears in good condition after total of 4 hours of testing. Somewhat uneven lubricant-film buildup on teeth. Grinding marks still evident when lubricant film was scrapped off. Low rate of wear. Lubricant flow rate equalled 19 scoops per minute. Test showed it is not necessary to hone teeth.

NOTES:
(1) Pounds per linear inch of tooth face.
(2) Measuring pin having 0.4000-in. diameter used to determine gear-tooth wear at pitch diameter except as indicated otherwise according to the following:
(2a) Measuring pin having 0.3125-in. diameter to indicate dedendum wear.
(2b) Measuring pin having 0.7406-in. diameter to indicate addendum wear.

M-50 tool steel gears were tested in G-109 through G-110A. Test G-110A was a relatively successful 25-hour endurance run at a temperature of approximately 900° F, a load of 1000 ppi(tf), except for the initial 15 minutes when it was 400 ppi(tf), and speed was maintained at 7400 rpm. The final 2 hours of operation were interspersed with increases in drive power and tooth-vicinity temperature. Earlier inspections during the test revealed good lubricant films on the gears. Loss of backlash, abrasions on tooth tips, burrs and spotty filming were noted in the final visual inspection. The test gear materials were changed frequently to eliminate the possibility of test rig discrepancies influencing the comparative analysis of the data. This procedure allows for a reduction in the number of tests since once the data indicates the superiority of one material to the other the tests can be concentrated on the superior material.

Tests G-111 through G-112A were intended to be 25-hour endurance tests using M-2 tool steel gears and imposing the same test conditions as in G-110A. The best performance in the group was shown by G-112A, a temperature cycling test, which continued for about 6 hours. Although a light lubricant film was present on the gears, scoring, metal transfer, and heavy wear of the flanks was evident.

M-50 tool steel test gears were used in test G-113. The objective of the test was to operate for 25 hours or more at a speed of 7400 rpm under a load of 1000 ppi(tf) while cycling temperature from ambient to 900° F.

Forty-five hours of operation were accumulated. Sixteen and one-half temperature cycles were traversed during 41 hours of the test run. Generally, it was noted that as the test head temperature was increased, a rise in the drive-power requirement and tooth-vicinity temperature were indicated. It was observed after about 15 hours of temperature cycling that the tooth-vicinity temperature and the drive-power requirement could be reduced to normal by rapping the lubricant outlet port in the test-gear housing. It was indicated that a buildup of powder at the site of the port was preventing a continuous lubricant flow or changing the flow pattern.

After 25 hours of cycling operation, the outlet port was reworked introducing a 1-inch in place of a 3/8-inch opening. The test was continued but the rise in the temperature and drive power was not eliminated by the larger lubricant outlet.

The test was continued until 44 hours and 50 minutes had been accumulated when it was terminated due to the high noise level. Inspection revealed a light lubricant-film deposit on the tooth flanks. The dedenda were worn and metal transfer had occurred at the addenda. The edges and tips of the teeth were burred.

The general appearance of the test gears indicated that the supply of lubricant was not adequate. This condition caused the gear-tooth temperature to increase to the point where the thermal expansion eliminated the tooth backlash and the opposite tooth flanks had come in contact with each other.

Wear at three locations on the gears was measured with three sizes of measuring pins. The amounts of wear were indicated to be as follows:

	15-Tooth Gear (in.)	16-Tooth Gear (in.)
Addendum	0.0018	0.0004
Pitch Diameter	0.0014	0.0010
Dedendum	0.0035	0.0032

The performance curve for test G-113 is shown in Figure 14. The condition of the gear teeth after the test is shown in Figure 15.

Test G-114 was a 100-hour endurance attempt at a speed of 7400 rpm and a load of 1000 ppi(tf) with temperature being cycled from ambient to 900° F. The gear material was M-50 to tool steel which had been heat treated to a minimum hardness of R_c 60. The test was terminated after 98 hours and 25 minutes when it was considered to have achieved its objective.

A light load (440 ppi(tf)) break-in run at 796° F was first conducted for 1 hour during which the gears ran very well. Both instrumentation and noise level indicate that operation was smooth and very satisfactory. Average lubricant flow rate for the hour was 0.943 grams per minute.

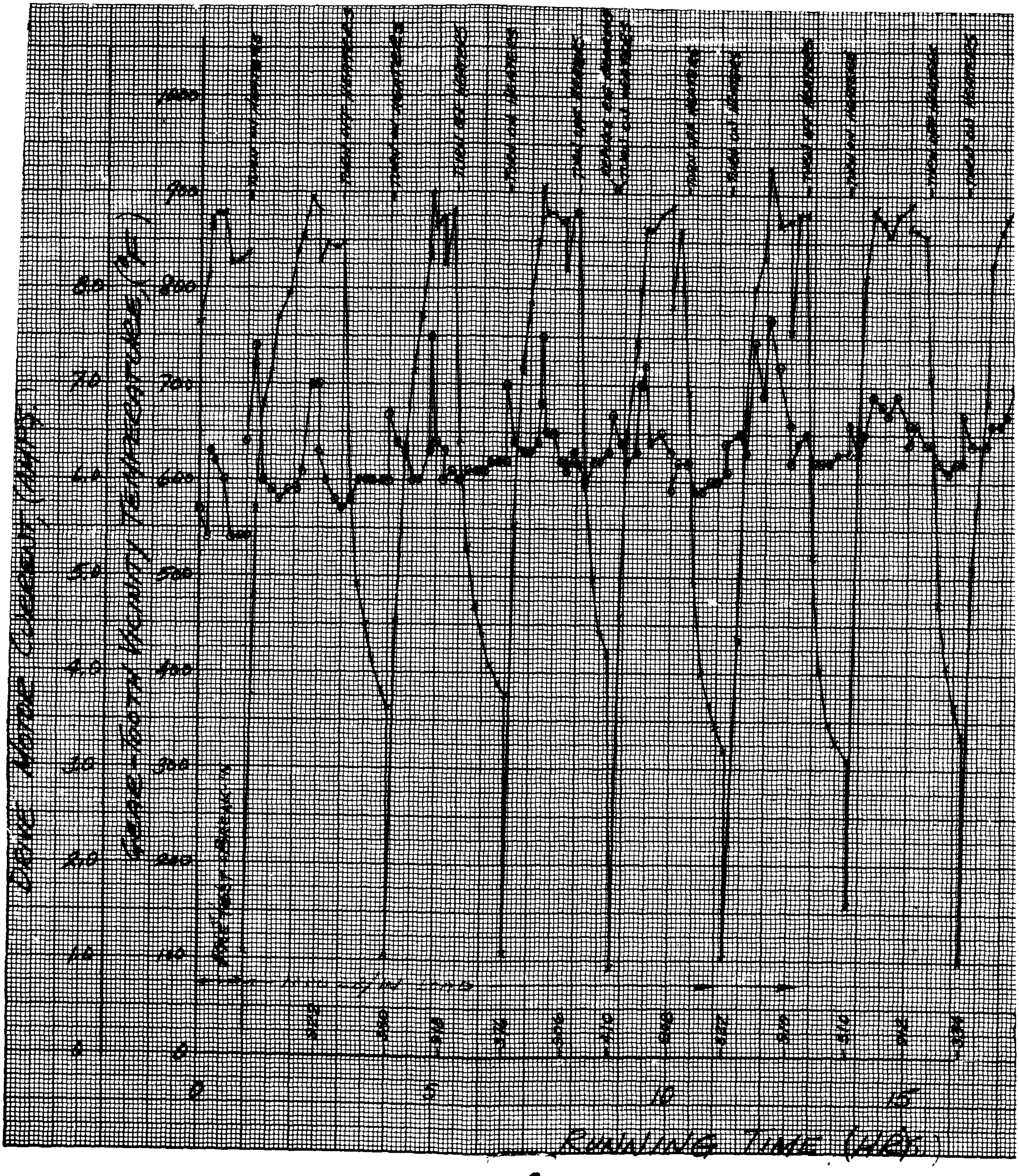
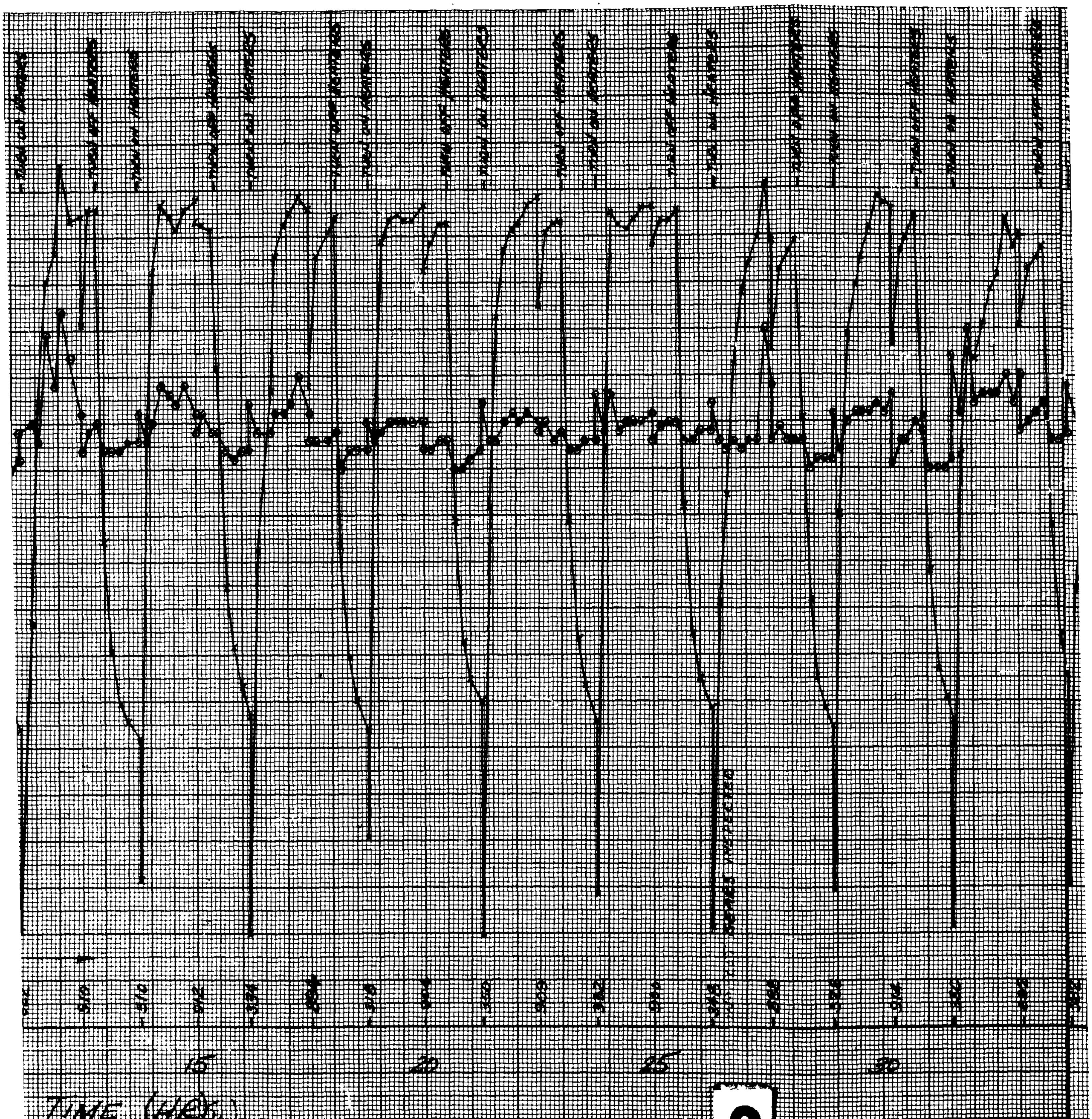


Figure 14. Test G-113 Performance Curve



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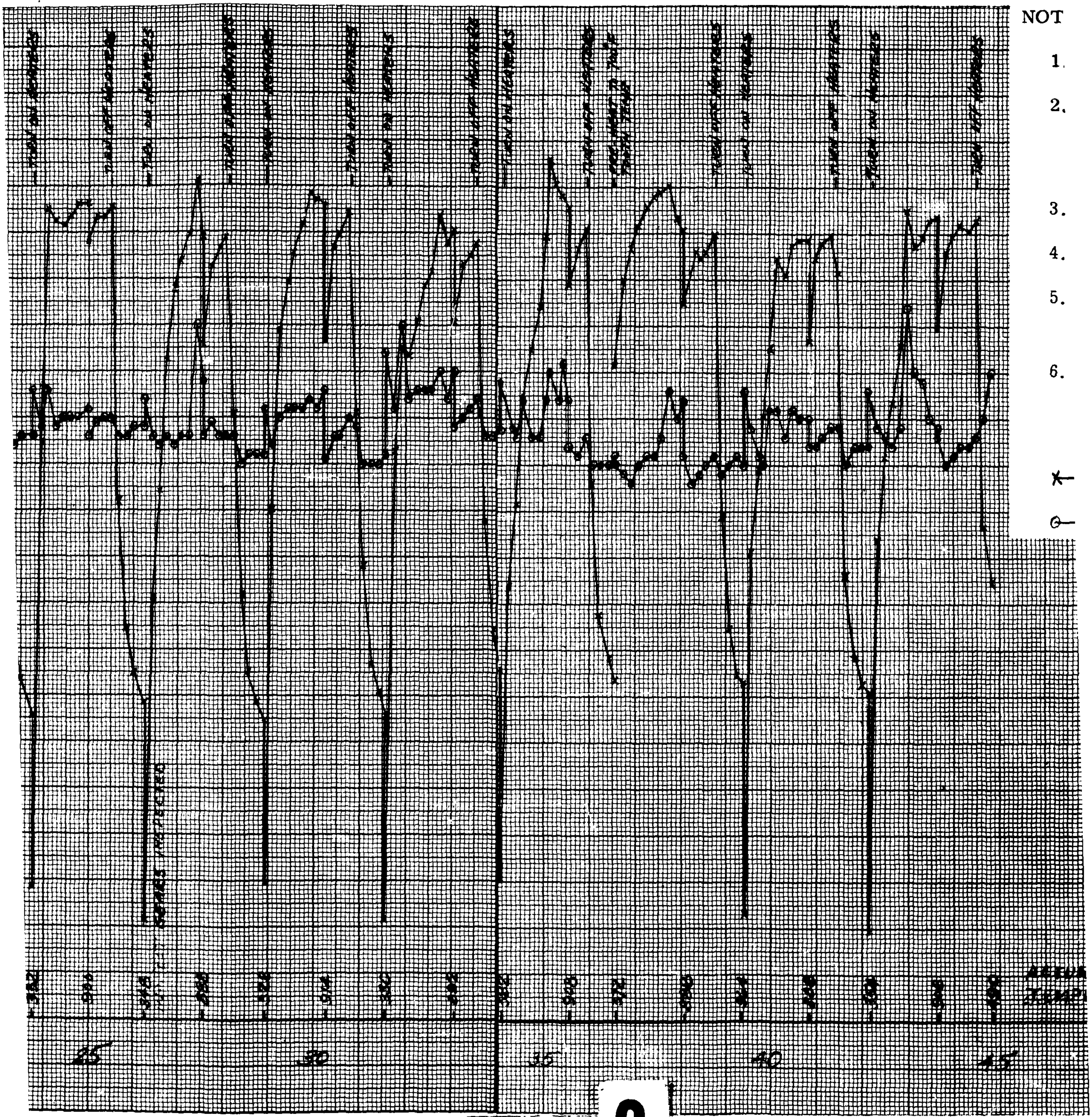

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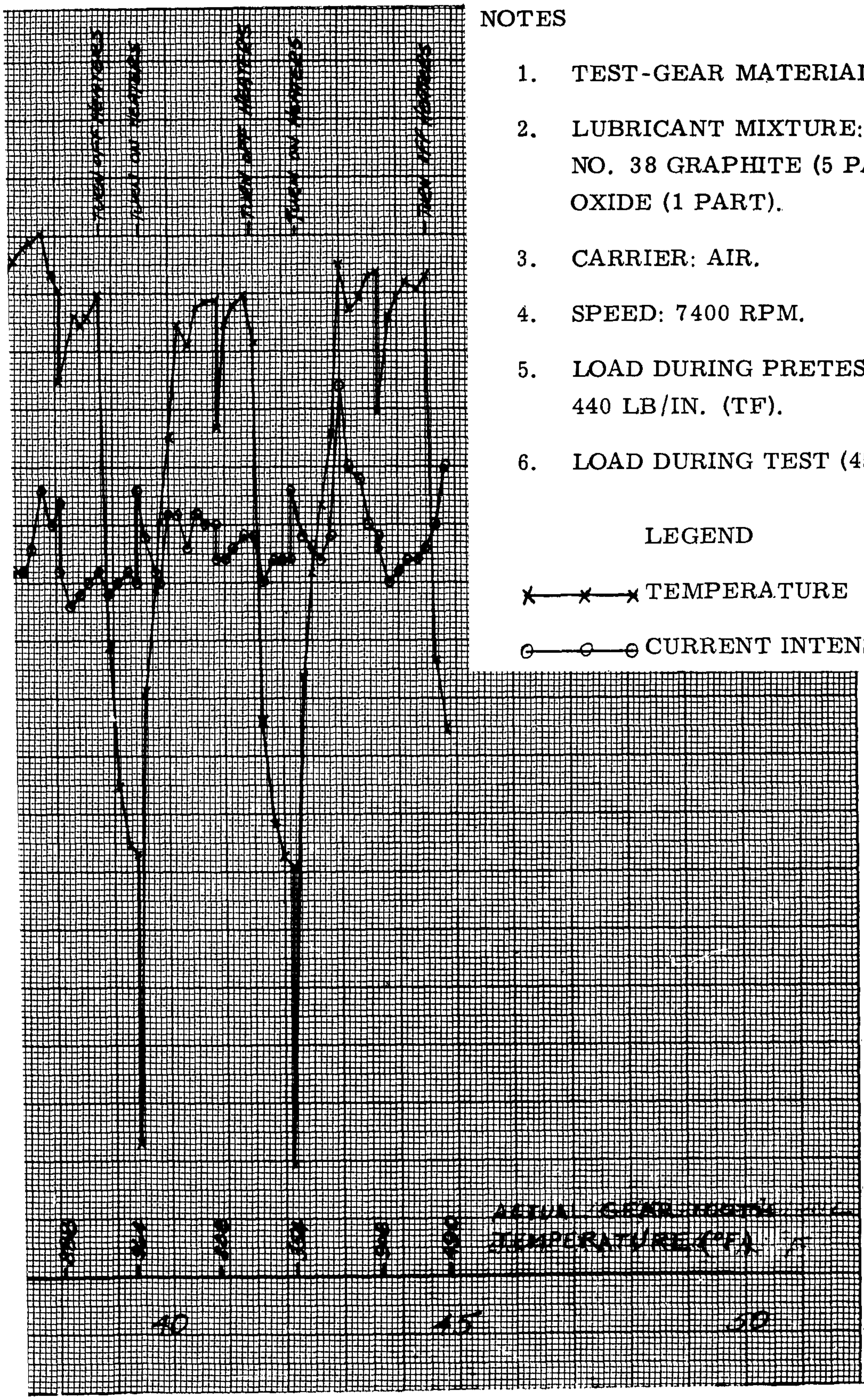


NOTES

1. TEST-GEAR MATERIAL: M-50 TOOL STEEL.
2. LUBRICANT MIXTURE: MICRONIZED ACHESON NO. 38 GRAPHITE (5 PARTS) PLUS CADMIUM OXIDE (1 PART).
3. CARRIER: AIR.
4. SPEED: 7400 RPM.
5. LOAD DURING PRETEST BREAK-IN (1 HR): 440 LB/IN. (TF).
6. LOAD DURING TEST (45 HR): 1000 LB/IN. (TF).

LEGEND

×—×—× TEMPERATURE

○—○—○ CURRENT INTENSITY

4

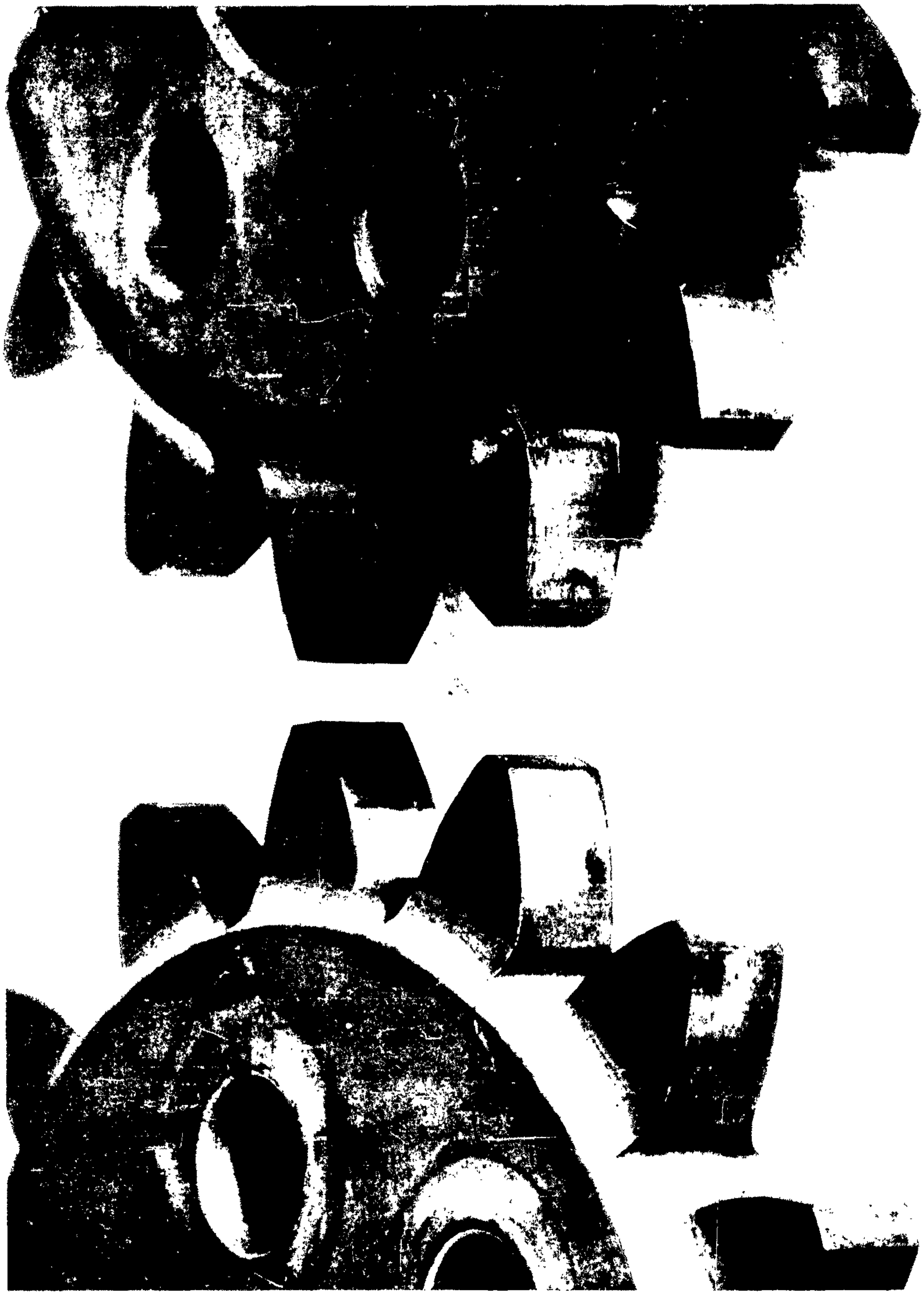


Figure 15. Test-Gear Set G-110A After 25 Hours of Test Operation

Following this hour, temperature cycling from ambient to 900° F and return was carried out for a period of 49 hours while under a load of 1000 ppi(tf). Also, 1 hour at ambient temperature and 1000 ppi(tf) was conducted. The gears ran well. Inspection revealed that the tooth flanks were in good condition covered by a good film of lubricant. Whereas previous testing had seldom produced a lubricant film on the dedenda, there was now some film present on them. Very slight burring and metal-transfer-type marks were noted across the flanks at the pitch diameter. Average lubricant flow rate for the 50-hour period was 1.07 grams per minute.

The test was continued for 18 additional temperature cycles in 47 hours 25 minutes during which the gears ran very smoothly. There was a light lubricant film covering the tooth flanks. The general condition of the flanks was good with slight abrasion marks apparent. A line was evident at the pitch line. The dedenda appeared to have more surface damage and wear than the addenda. The average lubricant flow rate for this interval was 1.04 grams per minute.

Over-pins measurements of the test G-114 gears at the various inspection intervals are listed in Table 3.

TABLE 3. TEST GEARS G-114 OVER-PINS MEASUREMENTS

Area Measured and Measuring Pin Diameter	0 Hours		50 Hours		98 Hr 25 Min	
	15 Tooth Gear	16 Tooth Gear	15 Tooth Gear	16 Tooth Gear	15 Tooth Gear	16 Tooth Gear
Addendum (0.7406 in.)	4.6120	4.8451	4.6119	4.8450	4.6119	4.8450
Pitch Line (0.4000 in.)	3.7279	3.9508	3.7263	3.9495	3.7255	3.9480
Dedendum (0.3125 in.)	3.4669	3.6868	3.4642	3.6842	3.4605	3.6805

Relative amounts of wear for the gears used in test G-114 are listed in Table 4.

TABLE 4. RELATIVE WEAR IN GEARS G-114

Wear Areas	50 Hours		98 Hr 25 Min	
	15 Tooth Gear	16 Tooth Gear	15 Tooth Gear	16 Tooth Gear
Addendum	0.0001	0.0001	0.0001	0.0001
Pitch Line	0.0016	0.0013	0.0024	0.0028
Dedendum	0.0027	0.0026	0.0064	0.0063

Figure 16 shows the 16-tooth gear used in test G-114. Figure 17 is the performance curve of test G-114.

Phase I elevated temperature evaluations, G109 through G-114, test data is tabulated in Table 5.

PHASE II TESTS

Phase II gears were subjected to high temperature tests to evaluate gears that had been specifically designed for high temperature powder lubrication operation. This included evaluation of gears manufactured from materials that had been screened and chosen as likely materials to survive the operating conditions.

These tests involved the operation of fine-pitch superalloy and tool-alloy gears at speeds to 15,550 rpm and temperatures in excess of 1000° F while under loads of 1000 ppi(tf). Typical Phase II test gears are shown in Figure 18. Phase II test data is tabulated in Table 6.

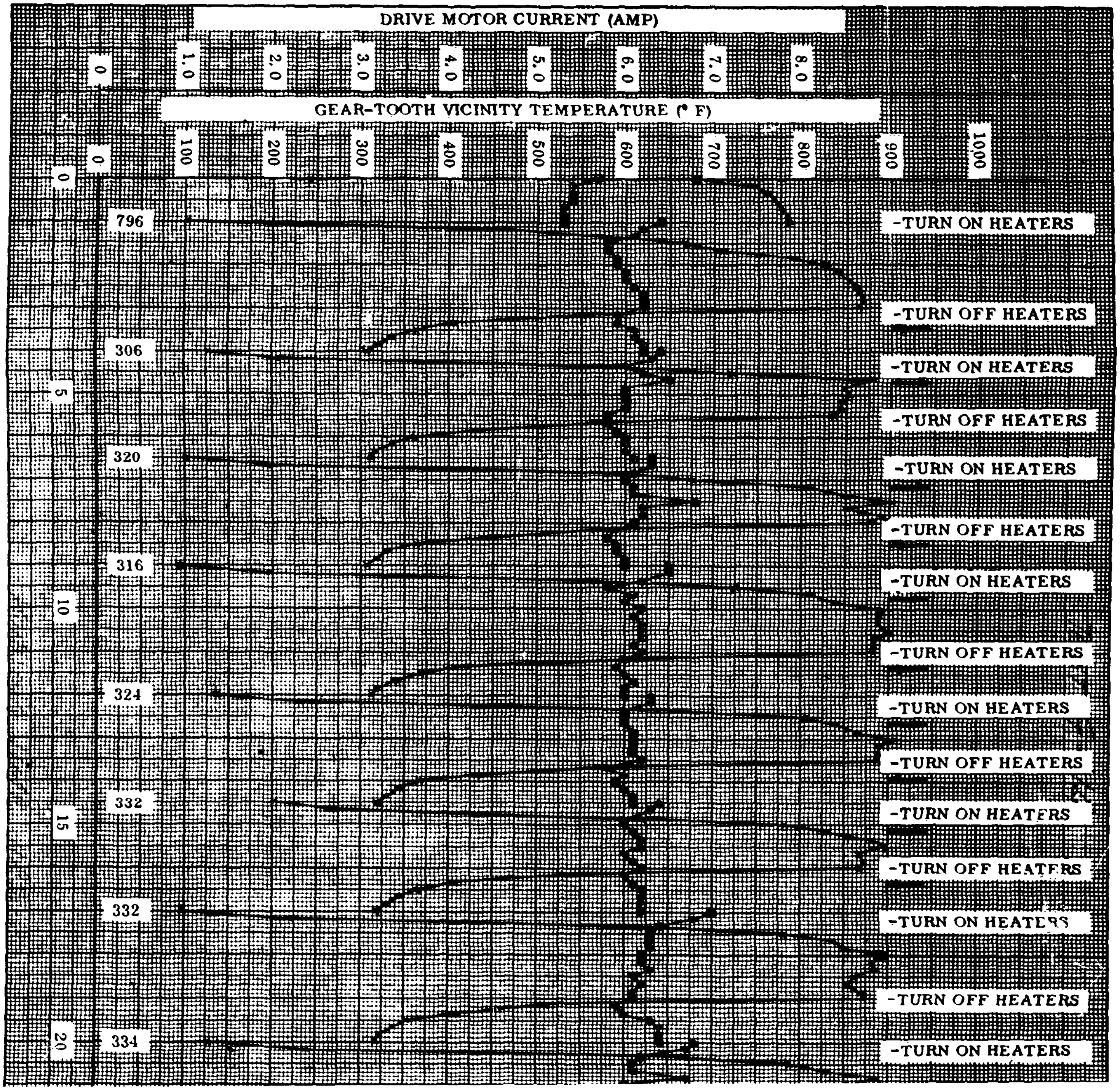
Haynes Stellite No. 151 Tests

Test G-118 was the first evaluation of gears fabricated from Haynes Alloy No. 151 using powder lubricants.

A break-in run was first conducted for 1 hour at 440 ppi(tf) and ambient temperature conditions. The gears operated very well. Visual inspection revealed slight abrasion-type marks on the tooth flanks and a light lubricant film. Gear-tooth temperatures varied from 90° F to 209° F. The average lubricant flow rate for this test interval was 1.27 grams per minute. An additional 4 hours of operation at ambient temperature and 440 ppi(tf) were conducted. Gear-tooth temperatures were recorded from 106° F to 250° F. The gears operated very well during this period. Visual inspection revealed slight abrasion marks (similar to the marks from the first test interval) and a light lubricant film. Wear of 0.001 inch maximum was measured over pins. The average lubricant flow rate for the 4-hour interval was 1.30 grams per minute.

Maintaining the 440 ppi(tf) load and the speed of 15,550 rpm, a 1-hour elevated temperature evaluation (from 692° F to 890° F) was conducted. The gears operated well and, when inspected, showed no worsening of the abrasion-type marks, a light lubricant film, and no measurable wear. The average lubricant flow rate for this test interval was 1.34 grams per minute.

Figure 16. Sixteen-Tooth Test Gear Used in G-114


DRIVE MOTOR CURRENT (AMP)
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
GEAR-TOOTH VICINITY TEMPERATURE (° F)
0
100
200
300
400
500
600
700
800
900
1000
0
5
10
15
20
796
306
320
316
324
332
332
334
-TURN ON HEATERS
-TURN OFF HEATERS
-TURN ON HEATERS
-TURN OFF HEATERS
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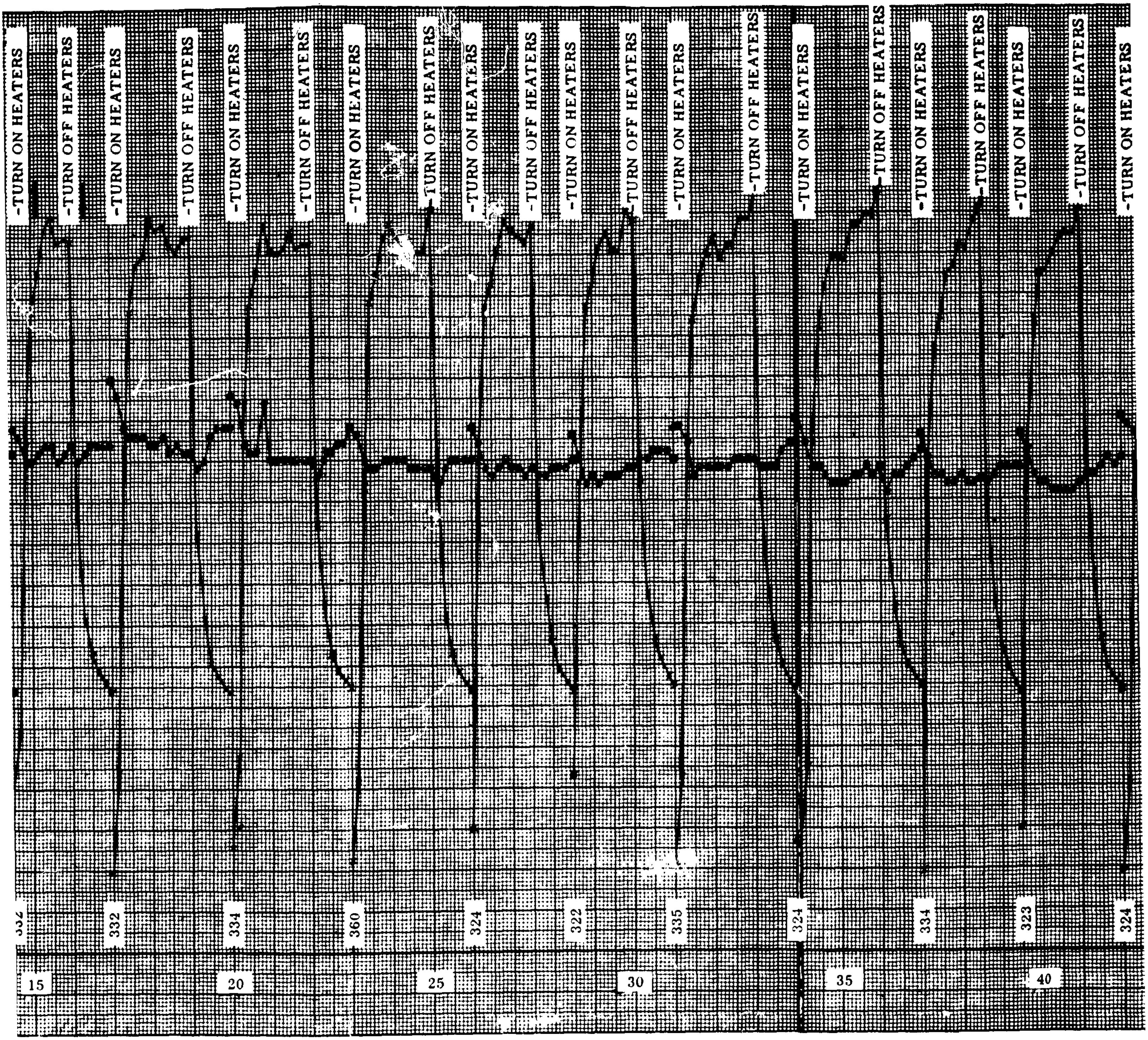
-TURN ON HEATERS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332
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360
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323
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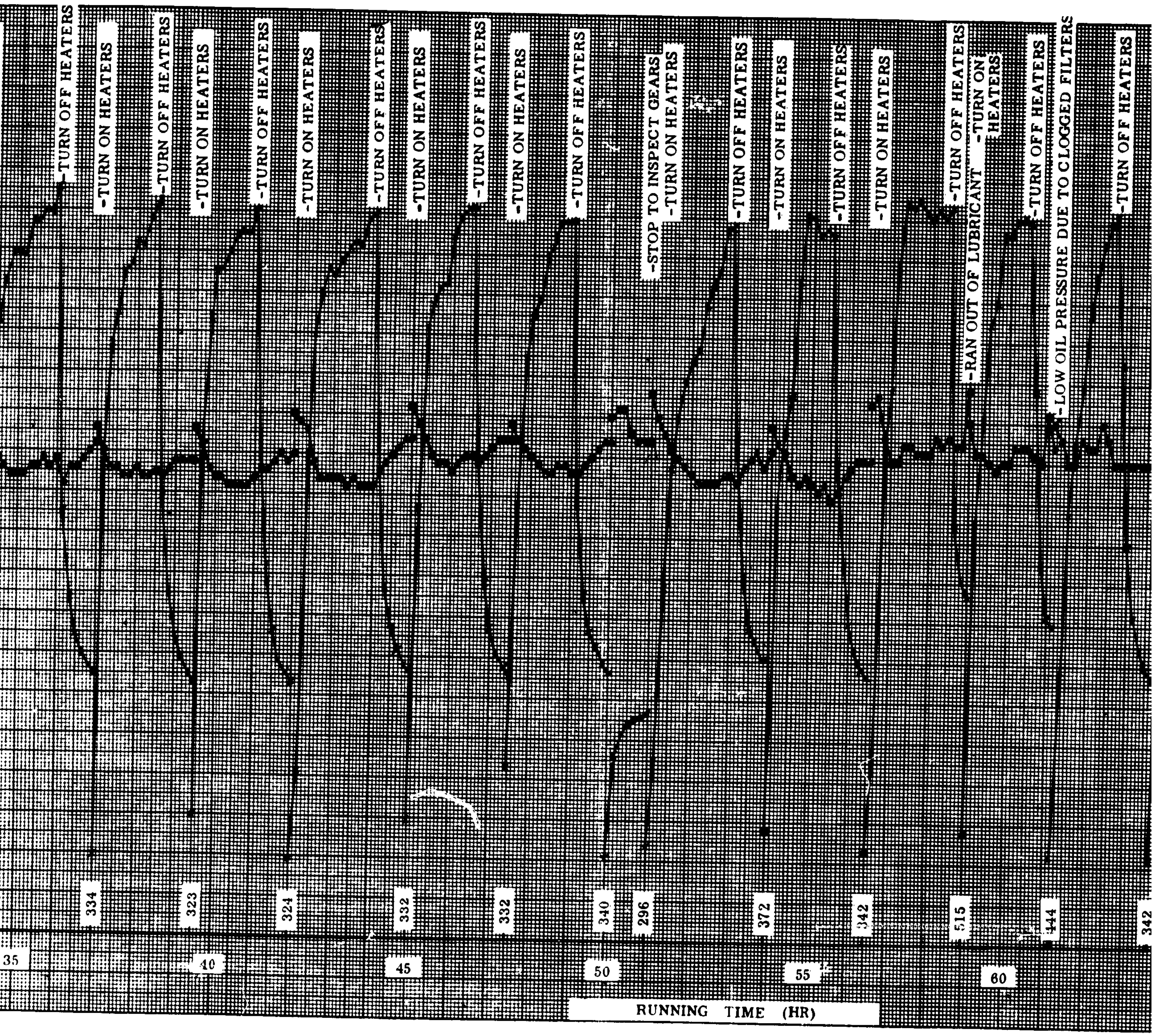
35
40

2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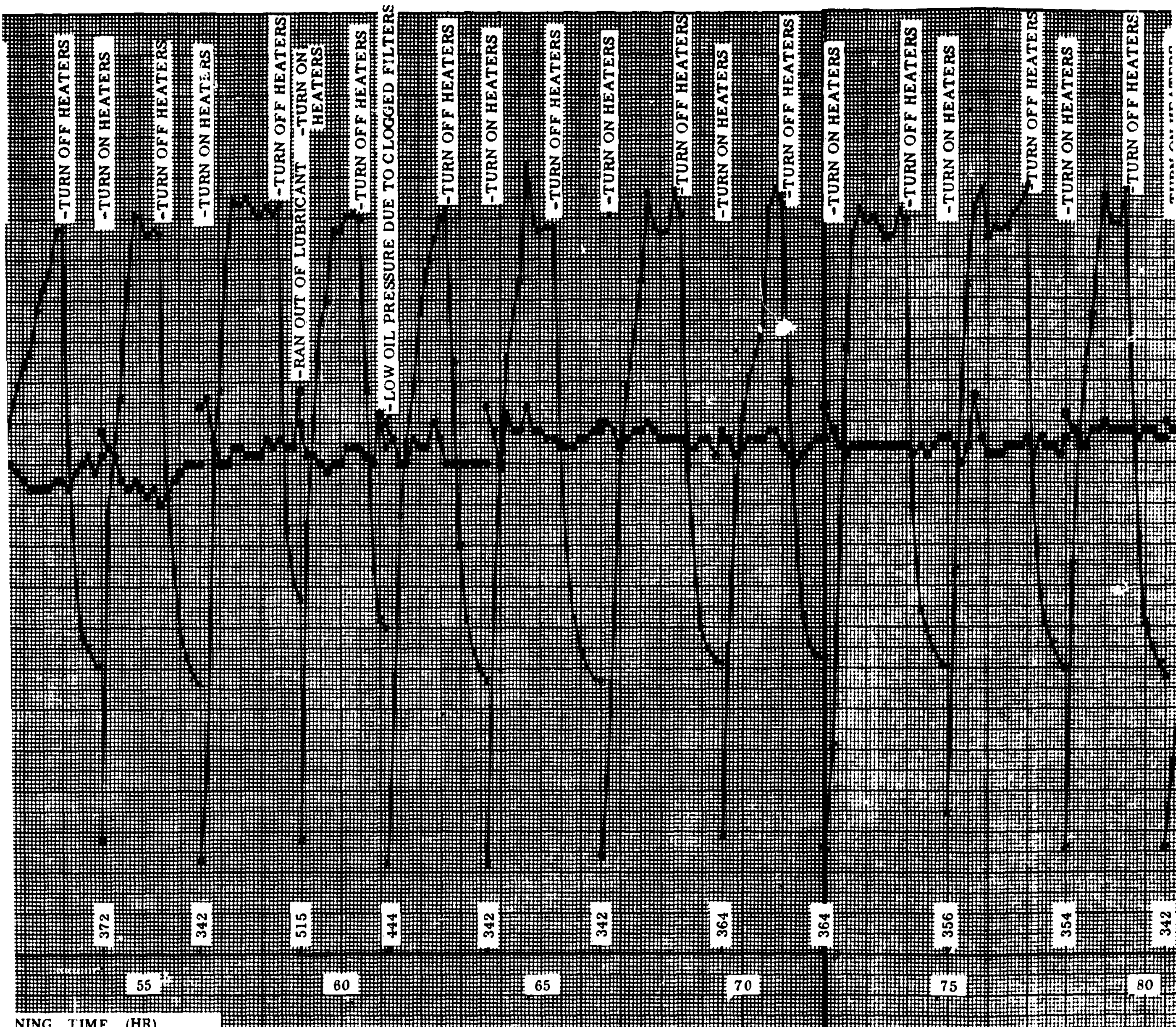
-TURN OFF HEATERS
-TURN ON HEATERS
-TURN OFF HEATERS
-TURN ON HEATERS
-TURN OFF HEATERS
-TURN ON HEATERS
-TURN OFF HEATERS
-STOP TO INSPECT GEARS
-TURN ON HEATERS
-TURN OFF HEATERS
-TURN ON HEATERS
-TURN OFF HEATERS
-TURN ON HEATERS
-TURN OFF HEATERS
-RAN OUT OF LUBRICANT
-TURN ON HEATERS
-TURN OFF HEATERS
-LOW OIL PRESSURE DUE TO CLOGGED FILTERS
-TURN OFF HEATERS
334
323
324
332
332
340
296
372
342
515
444
342
35
40
45
50
55
60
RUNNING TIME (HR)

3


-TURN OFF HEATERS
-TURN ON HEATERS
-TURN OFF HEATERS
-TURN ON HEATERS
-TURN OFF HEATERS
-RAN OUT OF LUBRICANT
-TURN ON HEATERS
-TURN OFF HEATERS
-LOW OIL PRESSURE DUE TO CLOGGED FILTERS
-TURN OFF HEATERS
-TURN ON HEATERS
-TURN OFF HEATERS
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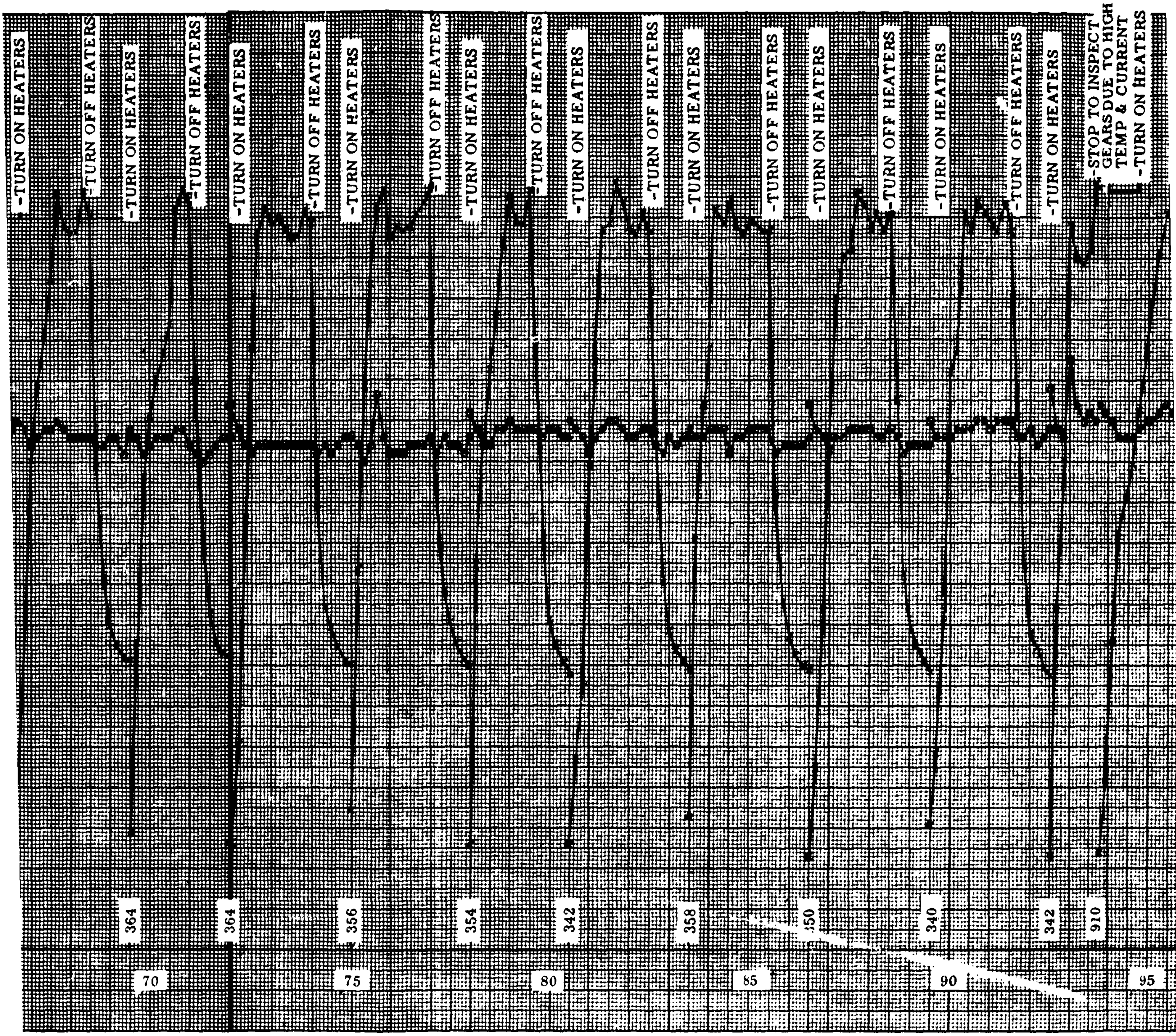
-TURN OFF HEATERS
-TURN ON HEATERS
-TURN OFF HEATERS
-TURN ON HEATERS
-TURN OFF HEATERS
-TURN ON HEATERS
-TURN OFF HEATERS
372
342
515
444
342
342
364
364
356
354
342
55
60
65
70
75
80
NING TIME (HR)

4


-TURN ON HEATERS
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-TURN OFF HEATERS
-TURN ON HEATERS
-TURN OFF HEATERS
-TURN ON HEATERS
-TURN OFF HEATERS
-TURN ON HEATERS
-STOP TO INSPECT GEARS DUE TO HIGH TEMP & CURRENT
-TURN ON HEATERS
364
364
356
354
342
358
350
340
342
910
70
75
80
85
90
95

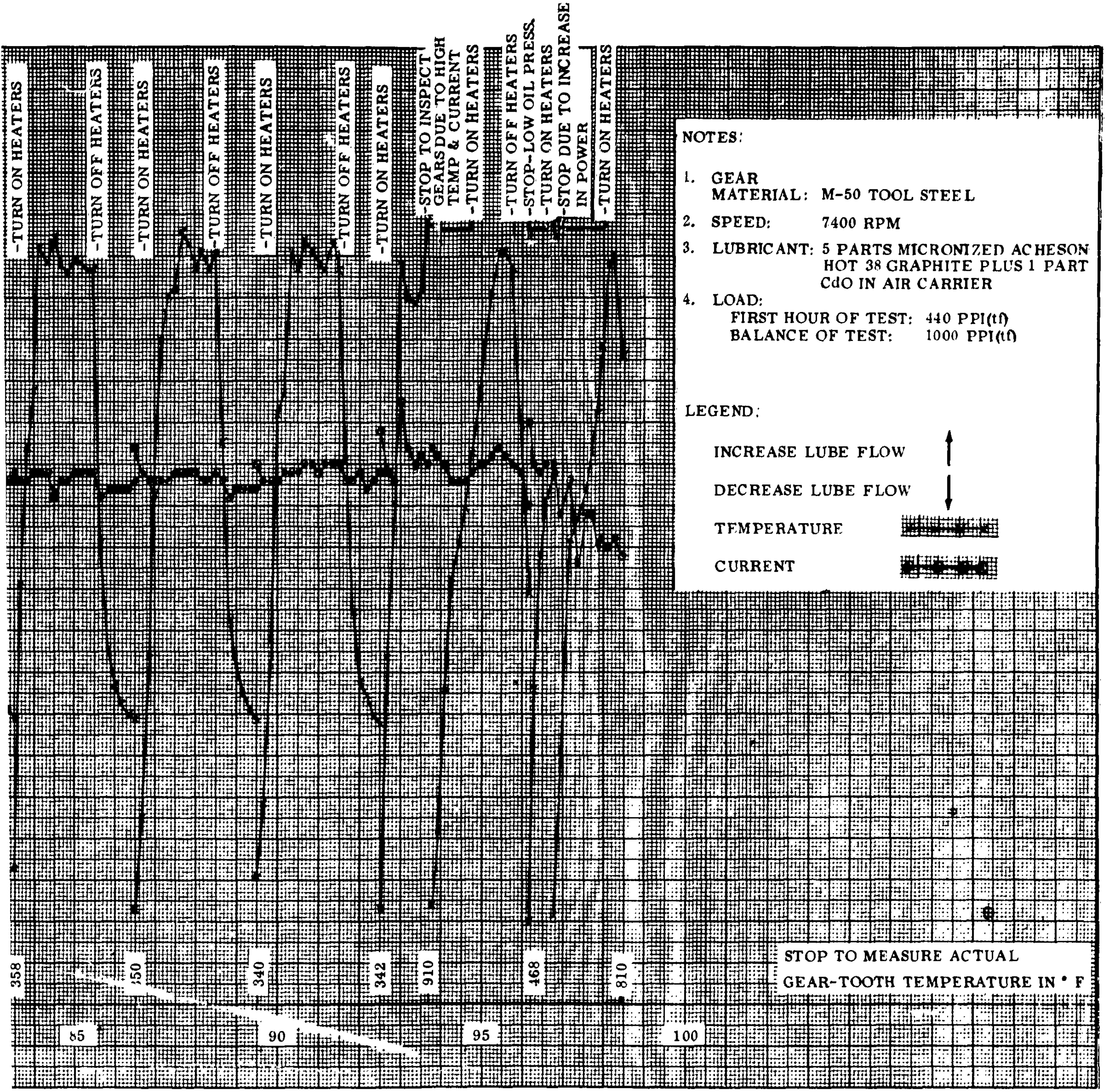


Figure 17. Test G-114 Performance Curve

6

TABLE 5. PHASE I ELEVATED TEMPERATURE EVALUATIONS

Test No.	Test Condtions and Objectives	Gear Material	Lubricant and Carrier	Load in lb/in. (tf) (1)	Speed (rpm)	Wear Measurements (2) 15-Tooth Gear Before	15-Tooth Gear After	16-Tooth Gear Before	16-Tooth Gear After	Time Interval (hr:min)	Lube Flow Rate (gm/min)	Tooth Temp (°F)	Remarks
G-109	Tool steel gears, graphite plus CdO lubricant at temperature of approximately 800°F. Tooth flanks not honed. Shields No. 1, No. 3 and No. 4 used.	M-50 tool steel (heat treated to R_c 60 min.)	5 parts micronized Acheson No. 38 graphite plus 1 part CdO in air	440	7400	3.4684 3.7291 4.6126	3.4684 3.7288 4.6128	3.6864 3.9503 4.8447		0:15		820	Good lubricant film on teeth. Gears in good condition with grind marks still evident. Lubricant flow rate equalled 19 scoops per minute.
				440	7400	3.4684 3.7288 4.6128	3.4684 3.7290 4.6129		3.6865 3.9504 4.8450	0:45		785	Run of 1 hour at 440 lb per in. (tf) completed. Good lubricant film on teeth. Cears in good condition with grind marks still evident. Lubricant flow rate equalled 19 scoops per minute.
				562	7400	3.4684 3.7290 4.6129	3.4684 3.7291 4.6128	3.6825 3.9504 4.8450		0:15		786	Good lubricant film on teeth. Gears in good condition, with grind marks still evident. Lubricant film rate equalled 19 scoops per minute.
				562	7400	3.4684 3.7291 4.6128	3.4683 3.7289 4.6127		3.6865 3.9505 3.8448	0:45		815	Run of 1 hour at 562 lb per in. (tf) completed. Good lubricant films. Fifteen-tooth gear in good condition with grind marks still evident. Sixteen-tooth gear slightly abraded near tooth tips, but grind marks were evident. Lubricant flow rate equalled 19 scoops per minute.
				720	7400	3.4683 3.7289 4.6127	3.4683 3.7291 4.6129	3.6865 3.9505 3.8448		0:15		790	Good lubricant film on teeth. Gears in good condition with grind marks still evident. Lubricant flow rate equalled 19 scoops per minute.
				720	7400	3.4683 3.7291 4.6129	3.4683 3.7290 4.6128		3.6865 3.9506 4.8450	0:45		820	Run of 1 hour at 720 lb per in. (tf) completed. Good lubricant films. Both gears in good condition with grind marks still evident on addenda but slight wear on dedenda. Slightly abraded at tips and dedenda of both gears; 15-tooth gear in a little better condition than 16-tooth gear. Intermittent noise increased approximately 7 minutes before end of test. Lubricant flow rate equalled 19 scoops per minute.

TABLE 5. PHASE I ELEVATED TEMPERATURE EVALUATIONS (Cont)

Test No.	Test Conditions and Objectives	Gear Material	Lubricant and Carrier	Load in lb/in. (tf) (1)	Speed (rpm)	Wear Measurements (2) 15-Tooth Gear Before	15-Tooth Gear After	16-Tooth Gear Before	16-Tooth Gear After	Time Interval (hr:min)	Lube Flow Rate (gm/min)	Tooth Temp (°F)	Remarks
G-109 (cont)				1000	7400	3.4683 3.7290 4.6129	3.4684 3.7290 4.6129	3.6865 3.9506 4.8450		0:15		790	Rig accidentally started without lubricator being turned on. About 30 seconds run without lubricant flow. Good lubricant film on teeth. Some abrasion on tooth flanks. Grind marks still evident on addenda, but not on dedenda. Lubricant flow rate equalled 20 scoops per minute.
				1000	7400	3.4684 3.7290 4.6129	3.4683 3.7291 4.6128		3.6866 3.9505 4.8449	0:45		805	Run of 1 hour at 1000 lb per in. (tf) completed. Run of 4 hours at 7400 rpm and approximately 800°F average temperature completed. Good lubricant film on teeth. <u>Fifteen-tooth gear</u>: Teeth in good condition. Grind marks still evident on approximately 50 per cent of addendum. No grind marks on dedendum. Some abrasion of flanks. <u>Sixteen-tooth gear</u>: Same general condition as 15-tooth gear but almost no grind marks left and slightly greater abrasion of tooth flanks. Lubricant flow rate equalled 20 scoops per minute.
				1000	7400	3.4683 3.7291 4.6128	3.4675 3.7287 4.6129	3.6866 3.9505 4.8449	3.6869 3.9495 4.8449	0:08		1004	Carrier-gas preheater installed in lubricant supply line. Gas flow reduced according to rotometer indication from 29 per cent to 14 per cent to provide higher gas temperature (620°F). Apparently reduced flow did not supply enough lubricant to gear meshing point. Gears ran well for about 5 minutes when drive power and noise level increased. Gears overheated due to high gas temperature. Loss of backlash indicated. Contact surfaces of both gears in poor condition. Brown scale on sides of gear teeth.
G-110	Familiarization with rig temperature gradients and readout since addition of lubricant and carrier gas preheater. Shields No. 1, No. 3, and No. 4 used.	M-50 tool steel (heat treated to R_c 60 min.)	5 parts micronized Acheson No. 38 graphite plus 1 part CdO in air	1000	7400	3.4679 3.7290 4.6129	3.4679 3.7290 4.6129	3.6863 3.9508 4.8452	3.6863 3.9508 4.8452	1:00		664 (3 704 800 857	Gears preheated with gear-box heaters and carrier gas preheater to 500°F. Gas flow at 28.5 per cent according to rotometer reading. Gear temperature measured at 15-minute intervals. Gears ran well. Good film of lubricant on addenda but little on dedenda of teeth. Line at pitch diameter. Some abrasion on both addenda and dedenda.

TABLE 5. PHASE I ELEVATED TEMPERATURE EVALUATIONS (Cont)

Test No.	Test Conditions and Objectives	Gear Material	Lubricant and Carrier	Load in lb/in. (tf) (1)	Speed (rpm)	Wear Measurements (2) 15-Tooth Gear Before	15-Tooth Gear After	16-Tooth Gear Before	16-Tooth Gear After	(hr:min)	Lube Flow Rate (gm/min)	Tooth Temp (°F)	Remarks
G-110A	Twenty-five hour endurance attempt at 900°F, 1000 lb/in. (tf) and 7500 rpm. Shields No. 1, No. 3, and No. 4 used.	M-50 tool steel (heat treated to R_c 60 min.)	5 parts micronized Acheson No. 38 graphite plus 1 part CdO in air	400	7400	3.4679 3.7290 4.6129		3.6863 3.9508 4.8452		0:15	0.900 throughout test	760	Break-in run at low load. Gears ran well.
				1000	7400					0:30		893	Gears ran well. Good lubricant film on contact surfaces.
				1000	7400		3.4679 3.7290 4.6129			0:30		864	Gears ran well. Fifteen-tooth gear removed for cleaning and inspection. Good lubricant film on addendum, little lubricant on dedendum. Line at pitch diameter. Slight abrasion on both addendum and dedendum.
				1000	7400					0:45		870	Gears ran well. No inspection.
				1000	7400					0:30		888	Gears ran well. No inspection.
				1000	7400					0:30		875	Gears ran well. No inspection.
				1000	7400					0:30		884	Gears ran well. No inspection.
				1000	7400					0:45		888	Gears ran well. No inspection.
				1000	7400					0:30		876	Gears ran well. No inspection.
				1000	7400		3.4677 3.7289 4.6131		3.6864 3.9507 4.8456	0:30		881	Run of 5 hours at 1000 lb per in. (tf) completed. Gears ran well. Addenda coated with good lubricant film. Film shiny, smooth, easily scraped off. Dedenda abraded. Some grinding marks still evident on addenda. Addenda show some abrasion. Sixteen-tooth gear in slightly better condition than 15-tooth gear.
				1000	7400					0:60		864	Gears ran well. No inspection.
				1000	7400					0:60		898	Gears ran well. No inspection.
				1000	7400					0:30		886	Gears ran well. No inspection.
				1000	7400					0:60		848	Gears ran well. No inspection. Low temperature caused by accidental shutoff of carrier-gas preheater for 10 minutes.
				1000	7400					0:60		910	Gears ran well. No inspection.

TABLE 5. PHASE I ELEVATED TEMPERATURE EVALUATIONS (Cont)

Test No.	Test Conditions and Objectives	Gear Material	Lubricant and Carrier	Load in lb/in. (tf) (1)	Speed (rpm)	Wear Measurements (2) 15-Tooth Gear Before	15-Tooth Gear After	16-Tooth Gear Before	16-Tooth Gear After	Time Interval (hr:min)	Lube Flow Rate (gm/min)	Tooth Temp (°F)	Remarks
G-110A (cont)				1000	7400		3.4676 3.7288 4.6129		3.6589 3.9507 4.8451	0:30		890	Run of 10 hours at 1000 lb per in. (tf) completed. Gears ran very well. Good lubricant film on addenda but little lubricant on dedenda. Dedenda abraded. Line at pitch diameter. Little change in surface condition during last 5 hours of testing.
				1000	7400					0:60		869	Gears ran well. No inspection.
				1000	7400					0:60		916	Gears ran well. No inspection.
				1000	7400					0:60		898	Gears ran well. No inspection.
				1000	7400					0:60		908	Gears ran well. No inspection.
				1000	7400					0:60		911	Gears ran well. No inspection.
				1000	7400					0:60		900	Gears ran well. No inspection.
				1000	7400					0:60		894	Gears ran well. No inspection.
				1000	7400					0:60		894	Gears ran well. No inspection.
				1000	7400					0:60		880	Gears ran well. No inspection.
				1000	7400		3.4678 3.7289 4.6130		3.6856 3.9511 4.8455	0:60		890	Run of 20 hours at 1000 lb per in. (tf) completed. Gears ran well. Good lubricant film on addenda, little on dedenda. Lubricant film shiny and smooth. Line at pitch diameter. Surface under lubricant in fair condition (abraded). Little change in surface condition during last 10 hours of testing.
				1000	7400					0:60		919	Gears ran well. No inspection.
				1000	7400					0:60		907	Gears ran well. No inspection.
				1000	7400					0:60		904	Gears ran well. No inspection.
				1000	7400					0:60		968	Relatively high drive power required during this test interval (6.7 amp instead of 5.5 amp). Thermocouple near gear teeth indicated high temperature (up to 960°F). Decreased gear-box heater power to decrease temperature. No excessive noise.

TABLE 5. PHASE I ELEVATED TEMPERATURE EVALUATIONS (Cont)

Test No.	Test Conditions and Objectives	Gear Material	Lubricant and Carrier	Load in lb/in. (tf) (1)	Speed (rpm)	Wear Measurements (2) 15-Tooth Gear Before	15-Tooth Gear After	16-Tooth Gear Before	16-Tooth Gear After	Time Interval (hr:min)	Lube Flow Rate (gm/min)	Tooth Temp (°F)	Remarks
G-110A (cont)				1000	7400		3.4675 (4) 3.7291 4.6129		3.6830(4) 3.9511 4.8453	0:60		904	Run of 25 hours at 1000 lb per in. (tf) completed. Gears ran well except during 24th hour. Good lubricant film on addenda, little on dedenda. Loss of backlash in 24th hour evidenced by rub on opposite flanks. Tooth flanks abraded. Tips of teeth burred. Wear of dedenda not measurable with pins due to burrs. Lubricant film is approximately 0.000 in. thick. Wear after 25 hours of testing: Dedendum 15-tooth gear - 0.0005 16-tooth gear - 0.0034 Addendum 15- tooth gear - 0.0000 16-tooth gear - 0.0000
G-111	Twenty-six hour endurance attempt at 1000 lb/in. (tf), 7500 rpm while cycling temperature from ambient to 950°F.	M-2 tool steel (heat treated to R_c 61.5 min.)	5 parts micronized Acheson No. 38 graphite plus 1 part CdO in air	440	7400	3.4660 3.7270 4.6112		3.6846 3.9486 4.8437		0:60	0.700 average	900	Break-in run at low load. Gears ran well. Flanks had a good lubricant film which was shiny and polished looking.
				1000	7400					1:10		Ambient to 868 (1/2 cycle)	Drive power increased from 6.0 to 7.0 amp and tooth-vicinity thermocouple indication increased from 874°F to 920°F at the end of 40 minutes of testing. Lubricant flow increased and heat reduced. Temperature indication returned to about 874°F.
				1000	7400					1:20		900 to ambient (1/2 cycle)	Gears ran well. Flanks in good condition with fair lubricant-film buildup.
				1000	7400					1:20		Ambient to 924 (1/2 cycle)	Drive power increased from 5.8 to 6.7 amp and tooth vicinity thermocouple temperature indication increased from 738°F to 770°F after 32 minutes of testing. Intermittent gear noise also noted. After increasing lubricant flow rate, reading returned to about 738°F.
				1000	7400					1:40		900 to ambient (1/2 cycle)	Gears ran well. Flanks in good condition with a fair lubricant-film buildup.

TABLE 5. PHASE I ELEVATED TEMPERATURE EVALUATIONS (Cont)

Test No.	Test Conditions and Objectives	Gear Material	Lubricant and Carrier	Load in lb/in. (tf) (1)	Speed (rpm)	Wear Measurements (2) 15-Tooth Gear Before	15-Tooth Gear After	16-Tooth Gear Before	16-Tooth Gear After	Time Interval (hr:min)	Lube Flow Rate (gm/min)	Tooth Temp (°F)	Remarks
G-111 (cont)				1000	7400		3.4624 3.7260 4.6105		3.6821 3.9476 4.8429	0:16		Ambient to 925	Drive power increased from 6.6 to 11.5 amp after 5 minutes of testing. Test rig shut down. Lubricant flow rate increased. Test rig restarted. Test rig shut down after 16 minutes due to rapid increases in drive power and tooth-vicinity temperature. Metallic particles in spent lubricant. Tooth flanks in poor condition. Heavy scoring, metal transfer and burring of tooth edges noted. Failure due to lack of lubricant. Teardown of lubricator revealed that metering wheel was contaminated with oil. Powder lubricant and oil mixture gummed scoops. Total test time: 6 hours, 46 minutes. Wear in order of 0.002 in. to 0.003 in.
G-111A	Twenty-five hour endurance attempt at 1000 lb/in. (tf), and 7500 rpm, while cycling temperature from ambient to 950°F.	M-2 tool steel (heat treated to R_c 61.5 min.) Opposite faces of test-gear set G-111.	3 to 1 micronized mixture of Acheson No. 38 graphite plus CdO with micronized Acheson No. 38 graphite added to make 5 to 1 mixture, used with air carrier.	440	7400	3.4624 3.7260 4.6105	3.4611 3.7259 4.6101	3.6821 3.9476 4.8429	3.6816 3.9475 4.8425	0:10	0.586	945	Intended to be break-in run at low load. Test stopped due to drive power fluctuation (6.2 to 6.9 to 8.0 to 5.5 amp) and increasing tooth-vicinity temperature (611 to 935°F) and noise. No lubricant film on teeth. Heavy scoring with metal transfer and burring of tooth edges. Heavy wear of dedenda.
G-112	Twenty-five hour endurance attempt at 1000 lb/in. (tf) and 7500 rpm while cycling temperature from ambient to 950°F.	M-2 tool steel (heat treated to R_c 61.5 min.)	3 to 1 micronized mixture of Acheson No. 38 graphite plus CdO with micronized Acheson No. 38 graphite added to make 5 to 1 mixture, used with air carrier.	440	7400	3.4662 3.7271 4.6115		3.6844 3.9485 4.8437		0:15	0.630	912	Intended to be break-in run at low load. Test stopped due to drive power fluctuation (5.3 to 6.3 to 6.5 to 6.8 to 5.1 amp), increasing noise level and fluctuating tooth-vicinity temperature. Flanks appeared to have run with insufficient lubricant. Suspect poor performance due to rate of lubricant flow or quality of lubricant mixture used, or both.
			5 parts micronized Acheson No. 38 graphite plus 1 part CdO in air	440	7400					0:45	0.463	892	Gears ran well during this test interval, but were noisy.

TABLE 5. PHASE I ELEVATED TEMPERATURE EVALUATIONS (Cont)

Test No.	Test Conditions and Objectives	Gear Material	Lubricant and Carrier	Load in lb/in. (tf) (1)	Speed (rpm)	Wear Measurements (2) 15-Tooth Gear Before	15-Tooth Gear After	16-Tooth Gear Before	16-Tooth Gear After	Time Interval (hr:min)	Lube Flow Rate (gm/min)	Tooth Temp (°F)	Remarks
G-112 (cont)				1000	7400		3.4665 3.7273 4.6110		3.6836 3.9485 4.8430	1:00		880	Lower noise level experienced than during previous test interval. Gears ran well. High drive power required after 10 minutes, which then decreased and held when heater temperatures decreased and lubricant-flow rate was increased. Good lubricant film formed on addenda. No lubricant on dedenda. Loss of backlash indicated, butnot enough to damage other faces. Slight burrs at tips and edges of teeth. Apparently lubricant used in test G-111A and first 15 minutes of test G-112 is not good. However, 25-hour test (G-110A) used lubricant flow rate of 0.9 gm per min, so low lubricant flow caused problem.
G-112A	Twenty-five hour endurance attempt at 1000 lb/in. (tf) and 7500 rpm while cycling temperature from ambient to 950°F.	M-2 tool steel (heat treated to R_c 61.5 min.) Opposite faces of test-gear set G-112.	5 parts micronized Acheson No. 38 graphite plus 1 part CdO in air	440	7400	3.4665 3.7273 4.6110		3.6836 3.9485 4.8430		1:00	0.524 average	880	Break-in run at low load. Gears ran well.
				1000	7400					1:00		Ambient to 879 (1/2 cycle)	Gears ran well. Drive power increased from 6.1 to 7.0 amp and tooth-vicinity temperature increased from 820°F to 840°F after 40 minutes. When heater temperatures were decreased, both conditions returned to normal.
				1000	7400					1:20		879 to 365 (1/2 cycle)	Gears ran well. Nothing unusual noted.
				1000	7400		3.4659 3.7270 4.6102		3.6819 3.9486 4.8421	2:30		Ambient to 900 to ambient (1 cycle)	Gears ran well. Drive power increased from 3.1 to 8.0 amp after 35 minutes. Reduced heater temperature and power requirement returned to 6.4 amp. Tooth flanks in poor condition. Light lubricant film buildup on both gears. Scoring, metal transfer and heavy wear of flanks of both gears noted, appeared to be caused by insufficient lubricant flow. Another possible problem may be inability of M-2 tool steel to withstand attrition. Total of 5 hours of temperature cycling completed.

TABLE 5. PHASE I ELEVATED TEMPERATURE EVALUATIONS (Cont)

Test No.	Test Conditions and Objectives	Gear Material	Lubricant and Carrier	Load in lb/in. (tf) (1)	Speed (rpm)	Wear Measurements (2) 15-Tooth Gear Before	15-Tooth Gear After	16-Tooth Gear Before	16-Tooth Gear After	Time Interval (hr:min)	Lube Flow Rate (gm/min)	Tooth Temp (°F)	Remarks
G-113	Twenty-five hour endurance attempt at 1000 lb/in. (tf) and 7500 rpm while cycling temperature to 900°F. (Same test conditions as in test G-110A with temperature cycling added.)	M-50 tool steel (heat treated to R_c 60 min.)	5 parts micronized Acheson No. 38 graphite plus 1 part CdO in air	440	7400	3.4688 3.7291 4.6129		3.6871 3.9507 4.8451		1:00	0.338 average	882	Break-in run at low load. Drive power increased from 5.4 to 6.3 amp and tooth-vicinity temperature increased from 813°F to 866°F after 13 minutes. Upon reducing heater temperature, original operating conditions returned. Gears ran well.
				1000	7400					1:30		Ambient to 922 (1/2 cycle)	Drive power increased from 6.4 to 7.2 amp. Tooth-vicinity temperature increased after 5 minutes. Reduced heater temperature and drive power decreased to 6.3 amp. Noise level and tooth-vicinity temperature decreased. After 1 hour and 10 minutes, drive power increased from 6.1 to 7.0 amp and tooth-vicinity temperature increased from 855°F to 900°F.
				1000	7400					1:30	0.338	922 to ambient (1/2 cycle)	Gears ran well. Tooth flanks in good condition.
				1000	7400		3.4688 3.7284 4.6128		3.6856 3.9501 4.8450	22:25	0.887	Ambient to 905 to ambient (9 cycles)	Total running time: 26 hours and 15 minutes. Total cycling time: 25 hours and 15 minutes. Total number of cycles completed: 10 Fair amount of lubricant-film buildup on tooth flanks. During increasing temperature phase of each of nine cycles, the following data were recorded: Cycle No. / Elapsed Time of Cycle (hr:min) / Tooth Vicinity Temp (°F) / Drive Power (amp) 1 / 0:52 / 832 / 6.0-7.5 2 / 0:42 / 850 / 6.3-7.5 3 / 0:35 / 800 / 6.3-7.2 4 / 0:30 / 800 / 6.3-7.5 5 / 0:30 / 880 / 6.3-6.9 6 / 0:40 / 860 / 6.4-7.0 7 / 0:40 / 874 / 6.3-6.5 8 / 0:40 / 856 / 6.3-6.6 9 / 0:20 / 876 / 6.4-6.8 Condition of tooth flanks generally good. Some metal transfer at dedenda. Slight burring at tips of teeth. During fifth cycle, it was

TABLE 5. PHASE I ELEVATED TEMPERATURE EVALUATIONS (Cont)

Test No.	Test Conditions and Objectives	Gear Material	Lubricant and Carrier	Load in ppi (tf) (1)	Speed (rpm)	Wear Measurements (2) 15-Tooth Gear Before	15-Tooth Gear After	16-Tooth Gear Before	16-Tooth Gear After	Time Interval (hr : min)	Lube Flow Rate (gm/min)	Tooth Temp (° F)	Remarks
G-113 (cont)													discovered that striking the lubricant outlet tube resulted in decreased tooth-vicinity temperature and drive power which indicated the outlet tube was clogged.
				1000	7400		3.4653 3.7277 4.6111		3.6839 3.9497 4.8447	18:35	0.856	Ambient to 900 to ambient (6-1/2 cycles)	Total running time: 44 hours and 50 minutes. Total cycling time: 41 hours and 5 minutes. Total number of cycles completed: 16-1/2 Test runs constant temperature: 1 hour at load of 440 ppi (tf) at temperature of 882° F. 2 hours and 10 minutes at load of 1000 ppi (tf) at temperature of 888° F. Test stopped due to high noise level. Sight lubricant film buildup noted. Dedenda worn. Metal transfer at addenda. Burring of edges and tips of teeth. Gears appear to have suffered from insufficient lubricant during increasing temperature phase of each of six cycles. The following data were recorded: Cycle No. / Elapsed Time of Cycle (hr:min) / Tooth-Vicinity Temp (° F) / Drive Power (amp) 1 / 1:03 / 847 / 6.3-7.5 2 / (Desirable conditions prevailed) 3 / 1:10 / 869 / 6.7-7.0 4 / 1:05 / 847 / 6.3-7.0 5 / (Desirable conditions prevailed) 6 / 0:50 / 876 / 6.2-7.7 Opposite tooth flanks made contact indicating loss of backlash.
G-114	One-hundred hour endurance attempt at speed of 7400 rpm, load of 1000 ppi (tf) and with temperature cycled from ambient to 900° F	M-50 tool steel (heat treated to R_c 60 min.)	5 parts micronized Acheson No. 38 graphite plus 1 part CdO in air	440	7400	3.4669 3.7279 4.6120		3.6868 3.9508 4.8451		0:60	0.943	796	Break-in run with low load imposed. Gears operated well.
				1000	7400		3.4642 3.7263 4.6119		3.6842 3.9495 4.8450	50:00	1.07	Ambient to 900°F and return 18 cycles + 1 hr at ambient temp	No increase in drive power indicated when tooth vicinity temperature increased during increasing temperature cycles. Tooth flanks appeared in good condition and coated with a lubricant film. (Some film on dedendum.) Slight burring, metal transfer, and mark across flanks at pitch line observed.
							3.4605 3.7255 4.6119		3.6805 3.9480 4.8450	47:25	1.04	Ambient to 900°F and return 18 cycles	Operated for a total of 98 hr 25 min. Gears in generally good condition. Mark found across flanks at pitch line, light lubricant film over flanks, slight abrasion marks on dedenda; in worse condition than addenda.

TABLE 5. PHASE I ELEVATED TEMPERATURE EVALUATIONS (Cont)

Test No.	Test Conditions and Objectives	Gear Material	Lubricant and Carrier	Load in ppi (tf) (1)	Speed (rpm)	Wear Measurements (2) 15-Tooth Gear Before	Wear Measurements (2) 15-Tooth Gear After	Wear Measurements (2) 16-Tooth Gear Before	Wear Measurements (2) 16-Tooth Gear After	Time Interval (hr:min)	Lube Flow Rate (gm/min)	Tooth Temp (°F)	
G-114 (cont)													The following is a list of gear-wear data after 98-1/2 hours:

	15 Tooth Gear	16 Tooth Gear
Addendum	0.0001	0.0001
Pitch Diameter	0.0024	0.0028
Dedendum	0.0064	0.0063

NOTES:

(1) Pounds per linear inch of tooth-face width.

(2) Measuring pins of three sizes used to determine wear listed above in the following order:

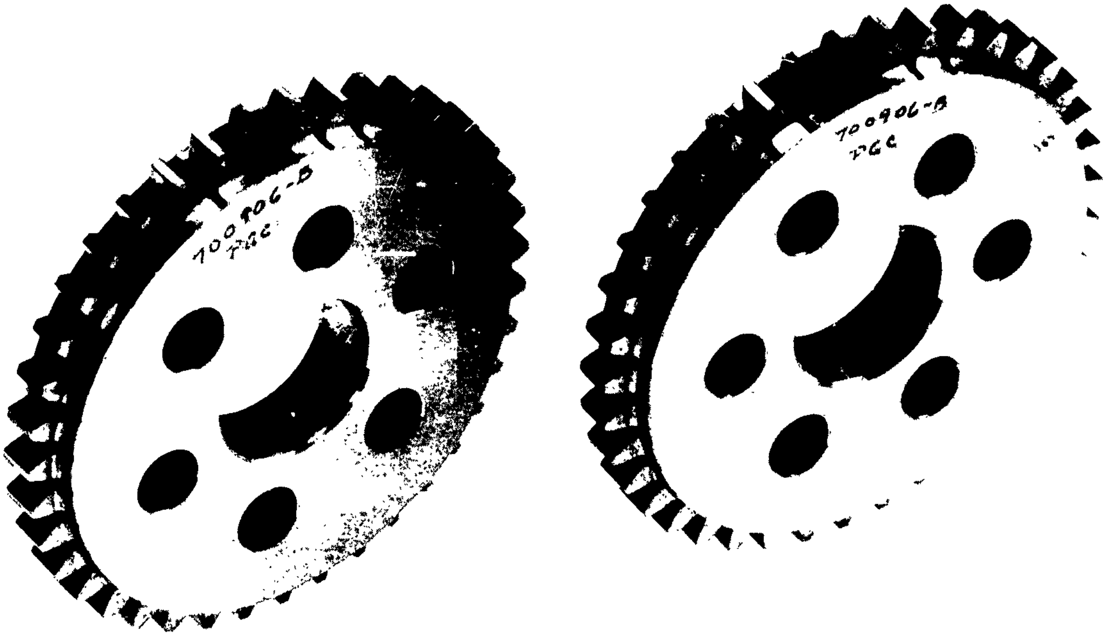
a. Dedendum measurement taken with 0.3125-in. diameter pin.

b. Pitch-diameter vicinity measurement taken with 0.4000-in. diameter pin.

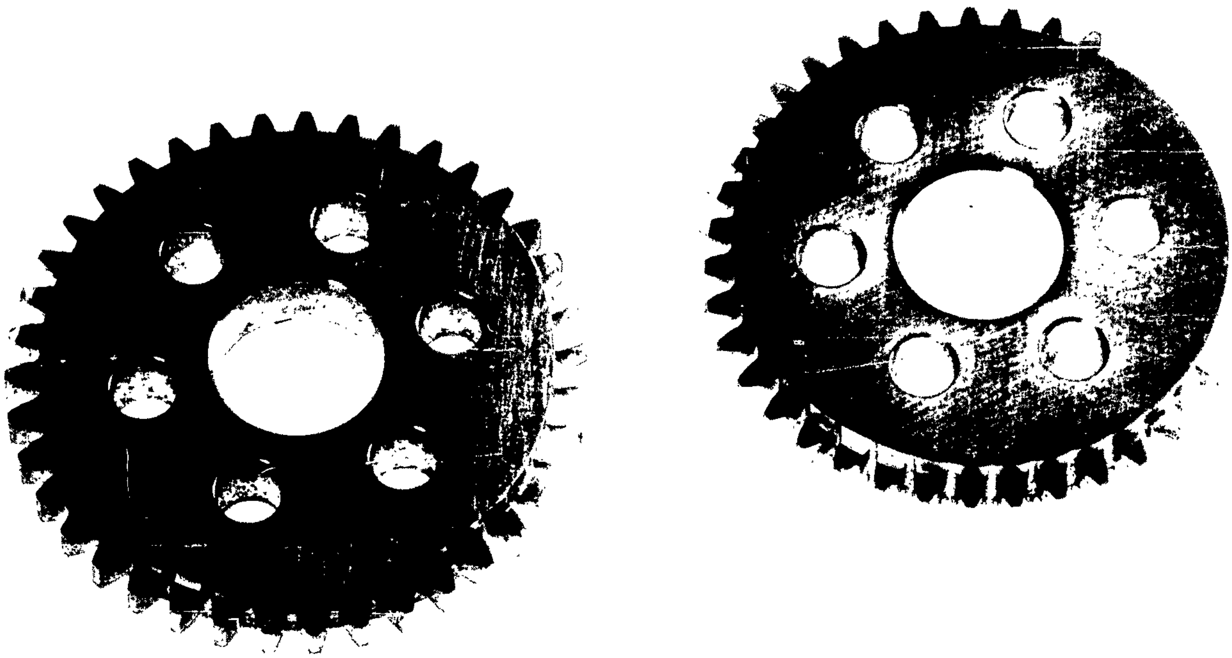
c. Addendum measurement taken with 0.7406-in. diameter pin.

(3) Each temperature listed for Test No. G-110 held for interval of 15 minutes.

(4) Measurements taken with lubricant film intact.



Front View



Rear View

Figure 18. Typical Gear Set Used in Phase II Tests

TABLE 6. PHASE II EVALUATIONS

Test No.	Objective of Test	Gear Material	Lubricant and Carrier	Load in ppi (tf) (1)	Speed (rpm)	Measurement Over Wires (2) Left-Hand Gear Teeth Before	Left-Hand Gear Teeth After	Right-Hand Gear Teeth Before	Right-Hand Gear Teeth After	Time Interval (hr;min)	Lube Flow Rate (gm/min)	Tooth Temp (° F)	Remarks
G-115	Rene '41 gear operation with powder lubricant.	AMS 5713 (Rene '41)	5 parts micronized Acheson No. 38 graphite plus 1 part CdO in air.	440	7400	3.4198 3.6442		3.4197 3.6448		0;42	0.3	234 (max)	Flanks badly scored and burred—appeared to suffer from lack of lubricant. Oil leakage past one rig-face seal clogged powder-inlet tube.
G-115A	Rene '41 gear operation at increased flow rate of powder lubricant.	AMS 5713 (Rene '41, opposite faces of gears G-115)	5 parts micronized Acheson No. 38 graphite plus 1 part CdO in air.	440	7400					1;00	1.23	248 (max)	Flanks badly scored and burred. Appeared to suffer from lack of lubricant since 1.23 gr/min flow believed to be sufficient, powder-inlet tube reworked to discharge into center of the mesh as corrective measure.
G-116	Determine effect of reworked powder lubricant inlet tube on Rene '41 gears.	AMS5713 (Rene '41)	5 parts micronized Acheson No. 38 graphite plus 1 part CdO in air.	440	7400	3.4205 3.6449		3.4200 3.6450		0;10	1.3	239 (max)	Flanks badly scored and burred. Appeared to suffer from lack of lubricant. (1.3 gr/min flow rate) Reworked shields to reduce radial clearance in relation to gears and centered powder-inlet tube on faces of teeth.
G-116	Determine effect of reduced shield clearance and re-positioned powder lubricant inlet tube on Rene '41 gears.	AMS 5713 (Rene '41, opposite faces of gears G-116)	5 part micronized Acheson No. 38 graphite plus 1 part CdO in air	440	7400					1;00	1.3	177 (max)	Gears ran well. Slight abrasion marks at tips, but no wear observed.
				440	10,350					1;00	1.3	205 (max)	Gears ran well. Abrasion marks which occurred in the first hour did not appear to worsen. Light lubricant film evident.
				440	10,350					1;00	1.28	500 to 760	Gears ran well. Abrasion marks slightly worse and light burr at tooth tips, light lubricant film evident.
				440	10,350					1;00	1.22	820 to 925	Test to establish maximum metal temperature attainable with rig and to determine Rene '41 capability at this temperature. Gears ran smoothly. Flanks appeared abraded with most damage located at tips.
G-117	Derive high-temperature operating data from Rene '41 gear tests.	AMS 5713 (Rene '41)	5 parts Acheson No. 38 graphite plus 1 part CdO in air.	440	10,350	3.4200 3.6447	3.4200 3.6447	3.4200 3.6445	3.4200 3.6445	1;00	1.13	810 to 950	Gears ran well. Slight abrasion marks. Light lubricant film evident. No measureable wear.
				440	10,350	3.4200 3.6447	3.4200 3.6447	3.4200 3.6445	3.4200 3.6445	5;00	0.95	822 to 990	Gears ran well. Slight abrasion marks. Light lubricant film evident. No measureable wear.

TABLE 6. PHASE II EVALUATIONS (Cont)

Test No.	Objective of Test	Gear Material	Lubricant and Carrier	Load in ppi (tf) (1)	Speed (rpm	Measurement Over Wires (2) Before	After	Before	After	Time Interval (hr:min)	Lube Flow Rate (gm/min)	Tooth Temp (°F)	Remarks
G-117 (cont)				440	10,350	3.4200 3.6447	3.4200 3.6447	3.4200 3.6445	3.4200 3.6445	5:00	0.75	812 to 880	Gears ran well. Slight abrasion marks. Light lubricant film evident. No measurable wear.
				440	15,550	3.4200 3.6447	3.4200 3.6447	3.4200 3.6445	3.4200 3.6445	1:00	0.89	762 to 830	Gears ran well. Some score marks present in addition to abrasion marks. Light lubricant film evident. No measureable wear.
				440	15,550	3.4200 3.6447	3.4180 3.6447	3.4200 3.6445	3.4190 3.6445	1:05	0.82	740 to 830	Gears ran well. Some scoring and abrasion marks. Most of surface damage at tips and dedenda. Little evidence of lubricant filming. Total: 13 hr 05 min of running time.
G-117-A	Evaluate Rene '41 gears at higher temperature levels (to 1050° F).	AMS 5713 (Rene '41, opposite faces of gears G-117).	5 parts Acheson No. 38 graphite plus 1 part CdO in air	440	15,550	3.4180 3.6447	3.4140 3.6447	3.4190 3.6445	3.4190 3.6440	0:30	1.41	920 to 1065	Abrasion marks at tips and scoring in vicinity of pitch diameter. Burred at tips. Gears demonstrated high rate of wear for only 30 minutes of operation under light load.

Notes:

(1) Pounds per linear inch of tooth-face width.

(2) Wear measurement over pins listed above in the following order:
   a. Pitch-diameter wear measured with 0.144-in. diameter pin.
   b. Tip wear measured with 0.210-in. diameter pin.

TABLE 6. PHASE II EVALUATIONS (Cont)

Test No.	Objective of Test	Gear Material	Lubricant and Carrier	Load in ppi (lf) (1)	Speed (rpm)	Measurement Over Wires (2) Left-Hand Gear Teeth Before	After	Right-Hand Gear Teeth Before	After	Time Interval (hr:min)	Lube Flow Rate (gm/min)	Tooth Temp (° F)	Remarks
G-118	Evaluate Haynes Alloy No. 151 gears with powder lubricants.	Haynes Alloy No. 151	5 parts Acheson No. 38 graphite plus 1 part CdO in air.	440	15,550	3.4208 3.6450	3.4200 3.6450	3.4210 3.6450		1:00	1.27	90 to 209	Gears ran well. Slight abrasion marks, light lubricant film evident.
				440	15,550	3.4200 3.6450	3.4200 3.6450	-- —	3.4200 3.6450	4:00	1.30	106 to 250	Gears ran well. Slight abrasion marks, light lubricant film evident. Little wear indicated.
				440	15,550	3.4200 3.6450	3.4200 3.6450	3.4200 3.6450	3.4200 3.6450	1:00	1.34	692 to 890	Gears ran well. Slight abrasion marks. Light lubricant film. No measurable wear indicated.
				440	15,550	3.4200 3.6450	3.4200 3.6450	3.4200 3.6450	3.4210 3.6460	5:00	1.15	850 to 1130	Gears ran well. Slight abrasion marks. Good lubricant film. No measureable wear indicated.
				562	15,550	3.4200 3.6450	3.4180 3.6450	3.4210 3.6460	3.4210 3.6460	5:00	1.25	836 to 1110	Gears ran well. Slight abrasion marks. Good lubricant film. Found 0.004 in. dedendum wear in one gear.
				629	15,550	3.4160 3.6450	3.4160 3.6450	3.4210 3.6460	3.4210 3.6460	5:00	1.14	832 to 1136	Gears ran well. Slight abrasion marks. Good lubricant film. No measureable wear indicated.
				685	15,550					4:05	1.06	832 to 1100	Gears ran well, until catastrophic tooth failure occurred. Approximately half of teeth stripped from each gear. Total: 25 hours of operation.

TABLE 6. PHASE II EVALUATIONS (Cont)

Test No.	Objective of Test	Gear Material	Lubricant and Carrier	Load in ppi (tf) (1)	Speed (rpm)	Measurement Over Wires (2) Left-Hand Gear Teeth Before	Left-Hand Gear Teeth After	Right-Hand Gear Teeth Before	Right-Hand Gear Teeth After	Time Interval (hr:min)	Lube Flow Rate (gm/min)	Tooth Temp (° F)	Remarks
G-119	Determination of validity of metal-fatigue theory in 25-hr test run in temperature range from 830 to 1050° F using Haynes Alloy No. 151 gears	Cobalt-base superalloy (Haynes Alloy No. 151)	5 parts Acheson No. 38 graphite plus 1 part CdO in air	685	15,500	3.4201 3.6448	- -	3.4210 3.6458	- -	0:15	1.21	832 to 905	Gears ran without incident. No inspection conducted.
				685	15,500					0:45	1.21	906 to 1010	Gears ran without incident. No inspection conducted.
				685	15,500					0:30	1.21	1020 to 1052	Gears ran without incident. No inspection conducted.
				685	15,500					0:30	1.21	1014 to 1084	Rig stopped when oil pressure to service gears and bearings dropped. Filter inspected and found to be clogged. Filter and tank cleaned, refilled with new supply of oil.
				685	15,500					0:40	1.01	828 to 1002	Following total run of 2 hr 40 min, service bearing seized on shaft. Teeth sheared on gears. Inspection revealed shaft shoulders to be out of line. Portion of tooth face 1/16 in. wide out of contact. New shaft bearing, seal, and seal washer installed in rig.
G-120	Rerun of G-119 using Haynes Alloy No. 151 gears	Cobalt-base superalloy (Haynes Alloy No. 151)	5 parts Acheson No. 38 graphite plus 1 part CdO in air	629	15,500	3.4199 3.6447	- -	3.4205 3.6453	- -	0:30	1.16	833 to 937	Sudden increase in power requirement indicated. Seal failure occurred. New seal installed.
				629	15,500					0:15	1.23	860 to 902	Satisfactory buildup of lubricant observed on teeth.
				629	15,500					0:45	1.23	904 to 1024	Gears ran without incident. No inspection conducted.
				629	15,500					1:00	1.23	906 to 1058	Gears ran without incident. No inspection conducted.
				629	15,500					1:00	1.18	892 to 1052	Gears ran without incident. No inspection conducted.
				629	15,500					1:00	1.18	964 to 1058	Gears ran without incident. No inspection conducted.
				629	15,500					1:00	1.07	956 to 1062	Gears ran without incident. No inspection conducted.
				629	15,500					0:30	1.07	1003 to 1068	Gears ran without incident. No inspection conducted.
				629	15,500					1:00	1.09	864 to 1050	Gears ran without incident. No inspection conducted.
				629	15,500					1:00	1.09	962 to 1064	Gears ran without incident. No inspection conducted.
				629	15,500	3.4216 3.6468	- -	3.4205 3.6450	3.4250 3.6485	1:00	1.13	876 to 1043	Hard black film observed on noncontacting surfaces of gears. No measurable tooth wear evident. Tooth roots zygloed but no defects found in roots of teeth after 9 hr of operation. Tooth flanks well coated with lubricant film. Slight abrasions noted beneath film.
				629	15,500					0:15	1.20	890 to 925	Gears ran without incident. No inspection conducted.
				629	15,500					0:45	1.20	876 to 989	Gears ran without incident. No inspection conducted.

TABLE 6. PHASE II EVALUATIONS (Cont)

Test No.	Objective of Test	Gear Material	Lubricant and Carrier	Load in ppi (tf) (1)	Speed (rpm)	Measurement Over Wires (2) Left-Hand Gear Teeth Before	Left-Hand Gear Teeth After	Right-Hand Gear Teeth Before	Right-Hand Gear Teeth After	Time Interval (hr:min)	Lube Flow Rate (gm/min)	Tooth Temp (° F)	Remarks
G-120	(continued)			629	15,500					2:00	1.20	852 to 1010	Gears ran without incident. No inspection conducted.
				629	15,500					2:00	1.12	867 to 968	Gears ran without incident. No inspection conducted.
				629	15,500					1:00	1.02	930 to 1032	Gears ran without incident. No inspection conducted.
				629	15,500	3.4230 3.6450	3.4220 3.6460	3.4260 3.6480	3.4240 3.6470	1:40	1.16	868 to 1573	Bearing on right-hand shaft of rig failed after 16-1/2 hr of testing--frozen to shaft. One orifice in oil-feed line clogged by caked oil--may have prevented sufficient lubrication. New parts installed. Total running time: 16 hr 40 min
				629	15,500					1:00	1.15	730 to 946	Gears ran without incident. Gears inspected at end of run. Gears well filmed.
				629	15,500					1:00	1.15	936 to 1008	Gears ran without incident. No inspection conducted.
				629	15,500	3.4266 3.4227	3.4270 3.4227	3.6460 3.6480	3.6465 3.6480	1:20	1.10	880 to 1017	Wear measurements were obtained with pins at 20 points (3). No measurable wear observed.
				629	15,500					2:00	1.15	964 to 1072	Gears ran without incident. No inspection conducted.
				629	15,500					2:30	1.13	924 to 1044	Inspection indicated that little lube film had been deposited on tips of gear teeth. Lube feed may have been reduced at end of interval. Total running time: 24 hr 30 min.
				629	15,500					1:10	1.16	806 to 1021	Lube flow stopped during run to determine if lube film would be worn off gear teeth. Power requirement increased after about 30 sec. Tooth flanks polished and marked with slight abrasions. Total running time: 25 hr 40 min.
				629	15,500					1:00	1.14	800 to 1003	Operated for 1 hr. Test rig oil filter clogged. Cleaned oil system and resumed testing.
				629	15,500					0:50	1.14	866 to 1018	Gears ran without incident. No inspection conducted.
				629	15,500					0:40	1.20	795 to 954	Operated for 40 min. Total running time: 28 hr 10 min.
				629	15,500					0:01	---	956	Gears failed after 1 min of operation. Inspection revealed failure of right-hand test-rig shaft which obscured cause. Further operation attempted. Rig oil system found to be functioning improperly after 5 min and oil system pressure drop noted. Motor-to-transmission coupling required replacement. Operation continued. Oil system continued to function improperly with reduction of oil pressure. Air leak suspected. Suction filter replaced with tube. Shafts and bearings replaced at service end of test rig. Left-hand oil seal found to leak air. Right-hand shaft found to have failed as a result of high bending stress. No material defect discovered. Oil filter continued to clog. Oil system rebuilt.

TABLE 6. PHASE II EVALUATIONS (Cont)

Test No.	Objective of Test	Gear Material	Lubricant and Carrier	Load in ppi (tf) (1)	Speed (rpm)	Measurement Over Wires (2) Left-Hand Gear Teeth Before	Left-Hand Gear Teeth After	Right-Hand Gear Teeth Before	Right-Hand Gear Teeth After	Time Interval (hr:min)	Lube Flow Rate (gm/min)	Tooth Temp (° F)	Remarks
G-121	Evaluation of Haynes No. 151 gear used with Rene' 41 gear (4)	One nickel-base super-alloy gear and one cobalt-base superalloy gear (Rene' 41 and Haynes Alloy No. 151)	5 parts micron-ized Acheson No. 38 graphite plus 1 part CdO in air	440	15,500					1:00	1.58	76 to 133	Gears inspected after first hour of operation. Found to have light coating of lubricant. Rough spot noted when gears were rotated by hand. Rene' 41 had good appearance. Abrasion marks on tooth flanks of Haynes No. 151 gear. Oil found mixed with powder lubricant in test head of rig.
				440	15,500					1:00	1.48	85 to 165	Gears ran without incident. No inspection conducted.
				440	15,550					1:00	1.48	148 to 188	Gears ran without incident. No inspection conducted.
				440	15,550					1:00	1.39	104 to 192	Gears ran without incident. No inspection conducted.
				440	15,550	3.4201 3.6459	3.4202 3.6459	3.4193 3.6446	3.4192 3.6446	1:00	1.39	162 to 200	Gears ran without incident. No inspection conducted.
				440	15,550	3.4198 3.6451	3.4197 3.6450	3.4191 3.6447	3.4191 3.6446	1:00	1.70	747 to 903	No lubricant film deposited on noncontacting surfaces. Haynes No. 151 gear only slightly and sporadically filmed. Better film on Rene' 41 gear. Abrasion marks on both gears. Golden brown coloration on both gears.
				440	15,550					1:00	1.17	786 to 899	Gears ran without incident. No inspection conducted.
				440	15,550					1:00	1.17	884 to 910	Gears ran without incident. No inspection conducted.
				562	15,550	3.4200 3.6500	3.4200 3.6449	3.4190 3.6448	3.4190 3.6448	1:00	1.18	760 to 898	Haynes No. 151 gear lightly filmed over about 40 per-cent of area. Rene' 41 gear well filmed.
				562	15,550					1:00	1.18	888 to 905	Gears ran without incident. No inspection conducted.
				562	15,550					1:00	1.23	782 to 898	Inspection of both gears revealed thin film of lubricant applied. Abrasion marks present on teeth of both but most noticeable on Haynes No. 151 gear. Line on Haynes No. 151, mark on Rene' 41 gears at pitch diameter.
				562	15,550					1:00	1.23	888 to 914	Gears ran without incident. No inspection conducted.
				562	15,550					1:00	1.38	814 to 909	Gears ran without incident. No inspection conducted.
				562	15,550					1:00	1.38	888 to 962	Gears ran without incident. No inspection conducted.
				562	15,550	3.4177 3.6452	3.4178 3.6452	3.4200 3.6450	3.4200 3.6451	1:00	1.34	860 to 906	Prior to turning on test rig, temperature was elevated to 1080° F (gear metal indication). Rig turned by hand. Operated freely. Backl- h was still present.
				629	15,550					0:10	---	786 to 808	Haynes No. 151 gear and right-hand shaft failed after 10 min of operation at 629 ppi (tf). Total test time: 15 hr 10 min.

TABLE 6. PHASE II EVALUATIONS (Cont)

Test No.	Objective of Test	Gear Material	Lubricant and Carrier	Load in ppi (tf) (1)	Speed (rpm)	Measurement Over Wires (2) Left-Hand Gear Teeth Before	Left-Hand Gear Teeth After	Right-Hand Gear Teeth Before	Right-Hand Gear Teeth After	Time Interval (hr:min)	Lube Flow Rate (gm/min)	Tooth Temp (°F)	Remarks
G-122	Evaluation of Rene' 41 test gears operating together	Nickel-base superalloy (Rene' 41)	5 parts Acheson No. 38 graphite plus 1 part CdO in air	440	15,500	3.4191 3.6448	3.4191 3.6447	3.4171 3.6420	3.4178 3.6420	0:25	1.06	93 to 148	Gears ran without incident. No inspection conducted.
										0:35	1.06	138 to 224	Wear rate high. Tooth tips and flanks marred. Lube film patchy. Lines appeared at pitch diameters of both gears.
G-122A	Evaluation of Rene' 41 test gears using opposite sides of G-122 gears	Nickel-base superalloy (Rene' 41)	5 parts Acheson No. 38 graphite plus 1 part CdO in air	440	10,350	3.4135 3.6394	3.4135 3.6395	3.4104 3.6431	3.4105 3.6431	0:05	---	108	No contact indicated over entire surface of tooth face. Opposite face of gears distorted due to tooth deformation suffered during previous test run. Test stopped due to rough run.
G-123	Continuation of Rene'41 gear evaluation	Nickel-base superalloy (Rene' 41)	5 parts Acheson No. 38 graphite plus 1 part CdO in air	440	10,350					1:00	0.90	98 to 140	Visually inspected gear teeth. Appearance good. Slight abrasion on tooth flanks and light lubricant film observed. Operation continued. Power requirement increase caused rig shutdown. Found oil leak around right-hand shaft due to faulty oil seal. Powder lube flow clogged. Deep abrasion marks noted on teeth, with slight burrs on teeth. Line appeared at pitch diameter.
				440	10,350					1:00	0.96	84 to 142	Gears ran without incident. No inspection conducted.
				440	10,350	3.4131 3.6401	3.4131 3.6401	3.4118 3.6390	3.4118 3.6390	0:50	0.96	128 to 220	Gears ran without incident. No inspection conducted.
				440	10,350					1:00	1.27	100 to 126	Gears ran without incident. No inspection conducted.
				440	10,350	3.4117 3.6395	3.4118 3.6395	3.4105 3.6386	3.4105 3.6387	1:00	1.27	94 to 148	Gears ran without incident. No inspection conducted.
				440	10,350					1:00	1.18	592 to 724	Gears ran without incident. No inspection conducted.
				440	10,350					1:00	1.18	716 to 748	Gears ran without incident. No inspection conducted.

NOTES

(1) Pounds per linear inch of tooth-face wear.

(2) Wear measurement over pins listed above in the following order:
a. Pitch diameter wear measured with 0.144 in. diameter pin
b. Tip wear measured with 0.210 in. diameter pin.

(3) Gear-tooth measurements taken between gear teeth at 20 points beginning after 20 hrs of operation in test G-120. Data given are averages of all points measured.

(4) Rene' 41 gear mounted in test rig on left-hand side.
Haynes Alloy No. 151 gear mounted in test rig on right-hand side.

TABLE 6. PHASE II EVALUATIONS (Cont)

Test No.	Objective of Test	Gear Material	Lubricant and Carrier	Load in ppi (tf) (1)	Speed (rpm)	Measurement Over Wires (2, 3) Left-Hand Gear Teeth Before	Left-Hand Gear Teeth After	Right-Hand Gear Teeth Before	Right-Hand Gear Teeth After	Time Interval (hr:min)	Lube Flow Rate (gm/min)	Tooth Temp (°F)	Remarks
G-123	Continuation of Rene '41 *gear evaluation*	Nickel-base *superalloy* (Rene '41)	5 parts Acheson No. 38 graphite plus 1 part CdO in air	440	10,350	3.4130 3.6397	3.4130 3.6397	3.4118 3.6389	3.4118 3.6389	1:00	0.90	98 to 140	Visually inspected gear teeth. Appearance good. Slight abrasion on tooth flanks and light lubricant film observed. Operation continued. Power requirement increase caused rig shutdown. Found oil leak around right-hand shaft due to faulty oil seal. Powder lube flow clogged. Deep abrasion marks noted on teeth, with slight burrs on teeth. Line appeared at pitch diameter.
				440	10,350					1:00	0.96	84 to 142	Gears ran without incident. No inspection conducted.
				440	10,350	3.4131 3.6401	3.4131 3.6401	3.4118 3.6390	3.4118 3.6390	0:50	0.96	128 to 220	Stopped to inspect gears. Appearance good.
				440	10,350					1:00	1.27	100 to 126	Gears ran without incident. No inspection conducted.
				440	10,350	3.4117 3.6395	3.4118 3.6395	3.4105 3.6386	3.4105 3.6387	1:00	1.27	94 to 148	Stopped to inspect gears. Some wear noted.
				440	10,350					1:00	1.18	592 to 724	Gears ran without incident. No inspection conducted
				440	10,350					1:00	1.18	716 to 746	Gears ran without incident. No inspection conducted.
				440	10,350					1:00	1.24	680 to 717	Gears ran without incident. No inspection conducted.
				440	10,350					1:00	1.24	690 to 732	Gears ran without incident. No inspection conducted.
				440	10,350	3.4119 3.6393	3.4119 3.6393	3.4101 3.6386	3.4100 3.6386	1:00	1.26	630 to 730	Stopped to inspect gears. Some wear noted.
				440	10,350					1:00	1.32	796 to 922	Gears ran without incident. No inspection conducted.
				440	10,350					1:00	1.32	860 to 925	Gears ran without incident. No inspection conducted.
				440	10,350					1:00	1.27	870 to 932	Gears ran without incident. No inspection conducted.
				440	10,350					1:00	1.38	854 to 924	Gears ran without incident. No inspection conducted.
				440	10,350	3.4133 3.6403	3.4132 3.6403	3.4107 3.6394	3.4107 3.6394	1:00	1.36	900 to 928	No. 1 measurement *over pins before* test run with gear prefilmed was 3.4140. After scraping film away, measuretment was 3.4125. Measurement after test run across same points before and after scraping away film were the same as previous measurements.
				440	10,350					1:00	1.48	880 to 965	Gears ran without incident. No inspection conducted.
				440	10,350					1:00	1.48	966 to 978	Gears ran without incident. No inspection conducted

TABLE 6. PHASE II EVALUATIONS (Cont)

Test No.	Objective of Test	Gear Material	Lubricant and Carrier	Load in ppi (tf) (1)	Speed (rpm)	Measurement Over Wires (2, 3) Left-Hand Gear Teeth Before	Left-Hand Gear Teeth After	Right-Hand Gear Teeth Before	Right-Hand Gear Teeth After	Time Interval (hr:min)	Lube Flow Rate (gm/min)	Tooth Temp (°F)	Remarks
G-123	(continued)			440	10,350					1:00	1.45	918 to 989	Gears ran without incident. No inspection conducted.
				440	10,350					1:00	1.45	933 to 968	Gears ran without incident. No inspection conducted.
				440	10,350	3.4210 3.6451	3.4210 3.6452	3.4182 3.4411	3.4182 3.4411	0:17	1.37	896 to 944	Great increase indicated in power requirement to drive test rig (10 amp). Power then dropped to 5.8 amp. Rig stopped. Gears failed. Cause appears to be fatigue. Total running time: 19 hr 7 min.
G-124	Evaluation of Haynes No. 6B gears	Cobalt-base tool alloy (Haynes Alloy No. 6B)	5 parts micron-ized Acheson No. 38 graphite plus 1 part CdO in air	440	10,350	3.4210 3.6452	3.4210 3.6452	3.4182 3.6442	3.4182 3.6442	1:00	1.60	80 to 138	Variac connected to test-rig motor supply to provide slow starting of rig motor.
				440	10,350					1:00	1.46	85 to 148	Gears removed from shafts and inspected. Grid marks not evident on right-hand gear; were evident on left-hand gear indicating no measurable wear.
				440	10,350					1:00	1.46	130 to 161	Gears ran without incident. No inspection conducted.
				440	10,350					1:00	1.50	108 to 159	Gears ran without incident. No inspection conducted.
				440	10,350					1:00	1.50	144 to 175	Gears ran without incident. No inspection conducted.
				440	10,350	3.4204 3.6452	3.4203 3.6453	3.4180 3.6440	3.4180 3.6440	1:00	1.54	678 to 737	Rig heaters set for 700° F. Test ran for 30 minutes before shutdown due to failure of air motor high pressure regulator. Clogged filter in line replaced. Test resumed.
				440	10,350					1:00	1.54	720 to 746	Gears ran without incident. No inspection conducted.
				440	10,350					1:00	1.42	662 to 723	Gears ran without incident. No inspection conducted.
				440	10,350					1:00	1.24	652 to 725	Gears ran without incident. No inspection conducted.
				440	10,350	3.4205 3.6451	3.4205 3.6451	3.4179 3.6440	3.4179 3.6440	1:00	1.21	878 to 1018	Gear measurements revealed little dimensional change.
				440	10,350					1:00	1.21	954 to 1019	Gears ran without incident. No inspection conducted.
				440	10,350					1:00	1.25	850 to 1020	Gears ran without incident. No inspection conducted.
				440	10,350					1:00	1.25	978 to 1022	Gears ran without incident. No inspection conducted.
				440	10,350					1:00	1.20	900 to 1015	Gears ran without incident. No inspection conducted. Gears completed 14 hours of test operation.
				562	10,350	3.4210 3.6460	3.4210 3.6460	3.4186 3.6442	3.4186 3.6442	1:00	1.30	875 to 1020	Load increased. Gears measured. Inspection reveals no flaws. Lubricant buildup on gears satisfactory.

TABLE 6. PHASE II EVALUATIONS (Cont)

Test No.	Objective of Test	Gear Material	Lubricant and Carrier	Load in ppi (tf) (1)	Speed (rpm)	Measurement Over Wires (2, 3) Left-Hand Gear Teeth Before	Measurement Over Wires (2, 3) Left-Hand Gear Teeth After	Measurement Over Wires (2, 3) Right-Hand Gear Teeth Before	Measurement Over Wires (2, 3) Right-Hand Gear Teeth After	Time Interval (hr:min)	Lube Flow Rate (gm/min)	Tooth Temp (°F)	Remarks
G-124	(continued)			562	10,350					1:00	1.30	966 to 1014	Gears ran without incident. No inspection conducted.
				562	10,350					0:30	1.30	955 to 1010	Gears ran without incident. No inspection conducted.
				562	10,350					1:00	1.37	854 to 980	Gears ran without incident. No inspection conducted.
				562	10,350					1:00	1.37	960 to 1013	Gears ran without incident. No inspection conducted.
				562	10,350					0:30	1.37	980 to 1014	Gears ran without incident. No inspection conducted.
				629	10,350	3.4220 3.6466	3.4220 3.6466	3.4199 3.6447	3.4199 3.6446	1:00	1.36	593 to 996	Load increased. Gears measured. Inspection reveals no flaws. Lubricant buildup on gears improved.
				629	10,350					1:00	1.36	842 to 996	Gears ran without incident. No inspection conducted.
				629	10,350					1:00	1.36	985 to 1016	Gears ran without incident. No inspection conducted.
				629	10,350					0:30	1.36	998 to 1007	Test stopped to inspect rig. Oil tanks removed, drained, and cleaned. Filters cleaned.
				629	10,350					1:00	1.30	904 to 1008	Gears ran without incident. No inspection conducted.
				629	10,350					1:00	1.30	995 to 1010	Gears ran without incident. No inspection conducted.
				685	10,350	3.4228 3.6471	3.4228 3.6470	3.4210 3.6451	3.4210 3.6450	0:30	1.30	1010 to 1020	Load increased. Gears measured and inspected. No wear or abrasions apparent.
				685	10,350					1:00	1.43	820 to 993	Gears ran without incident. No inspection conducted.
				685	10,350					1:00	1.43	1001 to 1015	Gears ran without incident. No inspection conducted.
				685	10,350					0:30	1.43	966 to 973	Gears ran without incident. No inspection conducted.
				685	10,350					1:00	1.60	905 to 1014	Gears ran without incident. No inspection conducted.
				685	10,350	3.4231 3.6474	3.4231 3.6473	3.4221 3.6455	3.4221 3.6456	1:30	1.60	968 to 1019	Measurements indicate increase in lubricant buildup.
				720	10,350					1:00	1.46	818 to 992	Load increased. Gears ran without incident. No inspection conducted.
				720	10,350					1:00	1.46	974 to 1010	Gears ran without incident. No inspection conducted.

TABLE 6. PHASE II EVALUATIONS (Cont)

Test No.	Objective of Test	Gear Material	Lubricant and Carrier	Load in ppi (tf) (1)	Speed (rpm)	Measurement Over Wires (2, 3) Left-Hand Gear Teeth Before	Left-Hand Gear Teeth After	Right-Hand Gear Teeth Before	Right-Hand Gear Teeth After	Time Interval (hr:min)	Lube Flow Rate (gm/min)	Tooth Temp (° F)	Remarks
G-124	(continued)			720	10, 350					1:30	1. 48	900 to 1005	Gears ran without incident. No inspection conducted.
				720	10, 350					1:30	1. 40	936 to 1021	Gears ran without incident. No inspection conducted.
				1000	10, 350	3. 4233 3. 6474	3. 4230 3. 6474	3. 4230 3. 6471	3. 4230 3. 6471	1:00	1. 45	860 to 984	Load increased. Gears measured. No damage or wear noted as a result of previous increase in load. Total of 35 hrs running time completed.
				1000	10, 350					1:30	1. 45	966 to 1022	Gears ran without incident. No inspection conducted.
				1000	10, 350					1:00	1. 38	1002 to 1017	Gears ran without incident. No inspection conducted.
				1000	10, 350	3. 4231 3. 6476	3. 4231 3. 6475	3. 4228 3. 6461	3. 4227 3. 6461	1:30	1. 38	904 to 1010	Gears measured. No appreciable change apparent from increased load. Small oil filters checked and found to be dirty during run. After 5 hrs rig stopped. Oil leak indicated in test-gear chamber. Seal and bearing replaced. Slight abrasions found on gear teeth.
				1000	10, 350					1:00	1. 50	830 to 952	Gears ran without incident. No inspection conducted.
				1000	10, 350					1:30	1. 50	940 to 1016	Gears ran without incident. No inspection conducted.
				1000	10, 350					1:00	1. 32	892 to 1024	Gears ran without incident. No inspection conducted.
				1000	10, 350					1:00	1. 32	997 to 1022	Gears ran without incident. No inspection conducted.
				1000	10, 350					2:30	1. 31	852 to 1010	Gears ran without incident. No inspection conducted.
				1000	10, 350					2:00	1. 25	885 to 1010	Test stopped after total running time of 49 hrs. New lubricator of increased capacity installed on rig. Calibrated at 1. 37 gr per min. Average temperature cycling interval estimated at 3 hrs.
				1000	10, 350	3. 4220 3. 6473	3. 4219 3. 6474	3. 4192 3. 6463	3. 4192 3. 6465	1:00	1. 20	956 to 1003	Gears ran without incident. No inspection conducted.
G-125	Temperature cycling tests to evaluate endurance of test gears under severe load	Cobalt-base tool alloy (Haynes Alloy No. 6B)	5 parts micronized Acheson No. 38 graphite plus 1 part CdO in air	440	10, 350	3. 4198 3. 6450	3. 4198 3. 6450	3. 4190 3. 6448	3. 4190 3. 6448	1:00	1. 32	720 to 920	Gears ran without incident. No inspection conducted. Gear load temporarily decreased.
				1000	10, 350					3:00	1. 54	80 to 1005 to 306	Temperature increased during initial 2 hrs of operation. Reduced during final hour. Actual gear tooth temperature at end of 3 hr run, 308° F. Rear rig bearings noisy. Replaced.
				1000	10, 350					3:00	1. 61	87 to 1015 to 326	Temperature increased by turning on heaters during initial 2 hrs of operation. Heaters turned off during final hour. Actual gear tooth temperature at end of 3-hr run, 332° F.
				1000	10, 350					0:10	1. 30	148 to 232	Heaters turned on after 10 min. Gears noisy. Power increased suddenly. Rig shut down. Gear teeth sheared.

TABLE 6. PHASE II EVALUATIONS (Cont)

Test No.	Objective of Test	Gear Material	Lubricant and Carrier	Load in ppi (tf) (1)	Speed (rpm)	Measurement Over Wires (2, 3) Left-Hand Gear Teeth Before	Left-Hand Gear Teeth After	Right-Hand Gear Teeth Before	Right-Hand Gear Teeth After	Time Interval (hr:min)	Lube Flow Rate (gm/min)	Tooth Temp (° F)	Remarks
G-126	Investigation to study effects of load on gear operation. (Load gradually increased during testing.)	Cobalt-base tool alloy (Haynes Alloy No. 6B)	5 parts micronized Acheson No. 38 graphite plus 1 part CdO in air	440	10,350	3.4190 3.6435	3.4190 3.6436	3.4200 3.6442	3.4200 3.6441	1:00	1.62	60 to 104	New gears installed and operated for 10 hrs at increasing loads.
				440	10,350					1:00	1.62	90 to 142	Gears ran without incident. No inspection conducted.
				440	10,350					1:00	1.62	708 to 804	Gears ran without incident. No inspection conducted.
				440	10,350					1:00	1.62	707 to 718	Gears ran without incident. No inspection conducted.
				440	10,350					1:00	1.55	946 to 1008	Gears ran without incident. No inspection conducted.
				440	10,350					1:00	1.55	820 to 1010	Main filter element replaced in rig oil system. Two small filters cleaned.
				629	10,350					2:00	1.65	980 to 1020	Extended test runs started. Gears ran without incident. No inspection conducted.
				1000	10,350					2:00	1.68	887 to 1014	Gears ran without incident. No inspection conducted.
				1000	10,350	3.4193 3.6444	3.4192 3.6443	3.4208 3.6456	3.4208 3.6457	1:00	1.17	882 to 1014	Gears removed and examined for wear and abrasions. None indicated.
				1000	10,350					4:00	1.17	892 to 1018	Gears ran without incident. No inspection conducted.
				1000	10,350	3.4194 3.6446	3.4193 3.6446	3.4190 3.6445	3.4190 3.6445	5:00	1.04	842 to 1018	Gears measured. Lubricant buildup increasing.
				1000	10,350	3.4200 3.6451	3.4200 3.6450	3.6451 3.6470	3.6450 3.6468	2:00	1.13	80 to 1115 to 360	Temperature cycling started following gear measurements after 20 hrs of testing.
				1000	10,350					3:00	1.12	74 to 1014 to 278	Temperature cycling continued. Gears ran without incident. No inspection conducted.
				1000	10,350					3:00	1.30	152 to 1011 to 300	Temperature cycling continued. Test rig disassembled to investigate cause of labyrinth seal rubbing on front end. Shafts required rework. New shafts installed. Oil system cleaned.
				1000	10,350	3.4199 3.6451	3.4199 3.6451	3.4209 3.6466	3.4209 3.6466	1:10	1.40	90 to 917	Gears ran without incident. No inspection conducted.
				1000	10,350					2:50	1.33	90 to 1017 to 368	Gears ran without incident. No inspection conducted.

TABLE 6. PHASE II EVALUATIONS (Cont)

Test No.	Objective of Test	Gear Material	Lubricant and Carrier	Load in ppi (tf) (1)	Speed (rpm)	Measurement Over Wires (2, 3) Left-Hand Gear Teeth Before	Left-Hand Gear Teeth After	Right-Hand Gear Teeth Before	Right-Hand Gear Teeth After	Time Interval (hr:min)	Lube Flow Rate (gm/min)	Tooth Temp (° F)	Remarks
G-126	(continued)			1000	10,350					3:00	1.21	92 to 1010 to 308	Noisey rear bearing caused halt of testing. Inspection of rig revealed oil leak. Four new bearings installed. Right-hand labyrinth seal replaced.
				1000	10,350					3:00	1.31	95 to 1026 to 281	Gears ran without incident. No inspection conducted.
				1000	10,350					3:00	1.34	128 to 1019 to 350	Oil pressure would not hold at 25 psig. Oil system of rig disassembled and cleaned. Fresh oil put into tanks.
				1000	10,350					3:00	1.37	90 to 1010 to 312	Gears ran without incident. No inspection conducted.
				1000	10,350					1:30	1.34	194 to 1014 to 330	Gears ran without incident. No inspection conducted.
				1000	10,350	3.4275 3.6462	3.4275 3.6463	3.4166 3.6457	3.4165 3.6455	3:00	1.41	87 to 1016 to 345	Ten complete temperature cycles completed during final 28-1/2 hrs of testing. At outset of eleventh cycle, power requirement increased to 8.5 amp. Rig stopped. Oil leak in test gear chamber found to have clogged powder lubricant supply to gear teeth. Small crack found at base of gear tooth. Total running time: 48-1/2 hrs.
G-127	Evaluation of Haynes No. 151 shot-peened gears	Cobalt-base superalloy (Haynes Alloy No. 151)	5 parts micronized Acheson No. 38 graphite plus 1 part CdO in air	440	10,350	3.4200 3.6450	3.4200 3.6450	3.4200 3.6450	3.4200 3.6450	1:00	1.30	82 to 120	Shot-peened gears measured and installed in test rig.
				440	10,350					1:00	1.30	112 to 142	Gears ran without incident. No inspection conducted.
				440	10,350					1:00	1.30	96 to 149	Gears ran without incident. No inspection conducted
				440	10,350	3.4190 3.6442	3.4190 3.6442	3.4187 3.6441	3.4186 3.6441	1:00	1.30	130 to 175	Towards end of fourth hour of operation, power requirement increased to 6.5 amp. Caused by oil leak into test-gear chamber. Two seals and three bearings replaced. Oil system cleaned. Wear indicated by gear measurements.
				562	10,350					2:00	1.41	640 to 720	Load on gears increased. Load checked each hour. Third hour of operation attempted during which teeth were sheared from gears.

NOTES

(1) Pounds per linear inch of tooth-face wear.

(2) Wear measurement over pins listed above in the following order:
a. Pitch diameter wear measured with 0.144 in. diameter pin.
b. Tip wear measured with 0.210 in. diameter pin.

(3) Gear-tooth measurements taken between gear teeth at 20 points. Data given are averages of all points measured.

The range of the test temperatures was now increased from 850° F to 1130° F, and a 5-hour evaluation was conducted at a load of 440 ppi(tf). Again gear operation was good. At inspection, the slight abrasion marks were still evident, but a good lubricant film had formed. The film was also evident on the nonrunning faces of the gears. There was no measurable wear during this test period in which the average lubricant flow rate was 1. 15 grams per minute.

A 5-hour evaluation was conducted at a load of 562 ppi(tf) and the gear tooth temperature ranged from 836° F to 1110° F. Gear operation remained good. Visual inspection showed the presence of slight abrasion-type marks as well as a good lubricant film on both running and nonrunning surfaces. The only wear recorded was a 0. 004 inch decrease in the over-pins measurement of the dedendum of one gear. The average lubricant flow rate for this test period was 1. 25 grams per minute.

The test load was then increased to 629 ppi(tf) and a 5-hour evaluation was conducted with gear tooth temperatures in the range from 832° F to 1136° F. Operation continued good. Visual inspection revealed the same well-distributed lubricant film and the slight abrasion-type marks. There was no increase in measurable wear. The average lubricant flow rate for this 5-hour interval was 1. 14 grams per minute.

A further increase in load to 685 ppi(tf) was applied for the purpose of conducting a 5-hour evaluation. Gear temperatures from 832° F to 1100° F were recorded. The gears operated well until at the 25 hour 5 minute point of total test time, a catastrophic tooth failure occurred. Approximately half the teeth were stripped from each gear. Figure 19 shows the test gears from test G-118 after failure. Figure 20 is the performance curve for test G-118.

Test G-119

With reference to the investigation of the failure of gears G-118, test G-119 was conducted to confirm previous test results. The speed of the test rig was adjusted to 15, 500 rpm and the load at 685 ppi(tf). It was decided to run the test for 25 hours operating in the temperature range from 830° F to 1050, F. The failure after 2-1/2 hours appeared to be caused by a weakness in the gear material. A check of the test rig, however, revealed a misalignment of the shafts on which the gears were mounted. Although the faces of the gear teeth were 1/4-inch wide, the greatest amount of contact between the teeth was about 1/16-inch. A turning moment was imposed upon the gears that would result in failure.

Test G-120

The objective of test G-120 was the same as the previous test. The speed adjustment was maintained at 15, 500 rpm and the temperature continued in the range from 830 to 1050° F. The load, however, was reduced to 629 ppi(tf). Duration of the test was intended to be 25 hours.

A thorough inspection of the gears was conducted after 9 hours of operation. In the visual check, it was observed that a hard black film had adhered to the noncontacting surfaces and the tooth flanks were well coated with a smooth lubricant film. When the lubricant film was removed from the teeth for wear measurements, no measurable

Figure 19. Gears G-118 After Failure

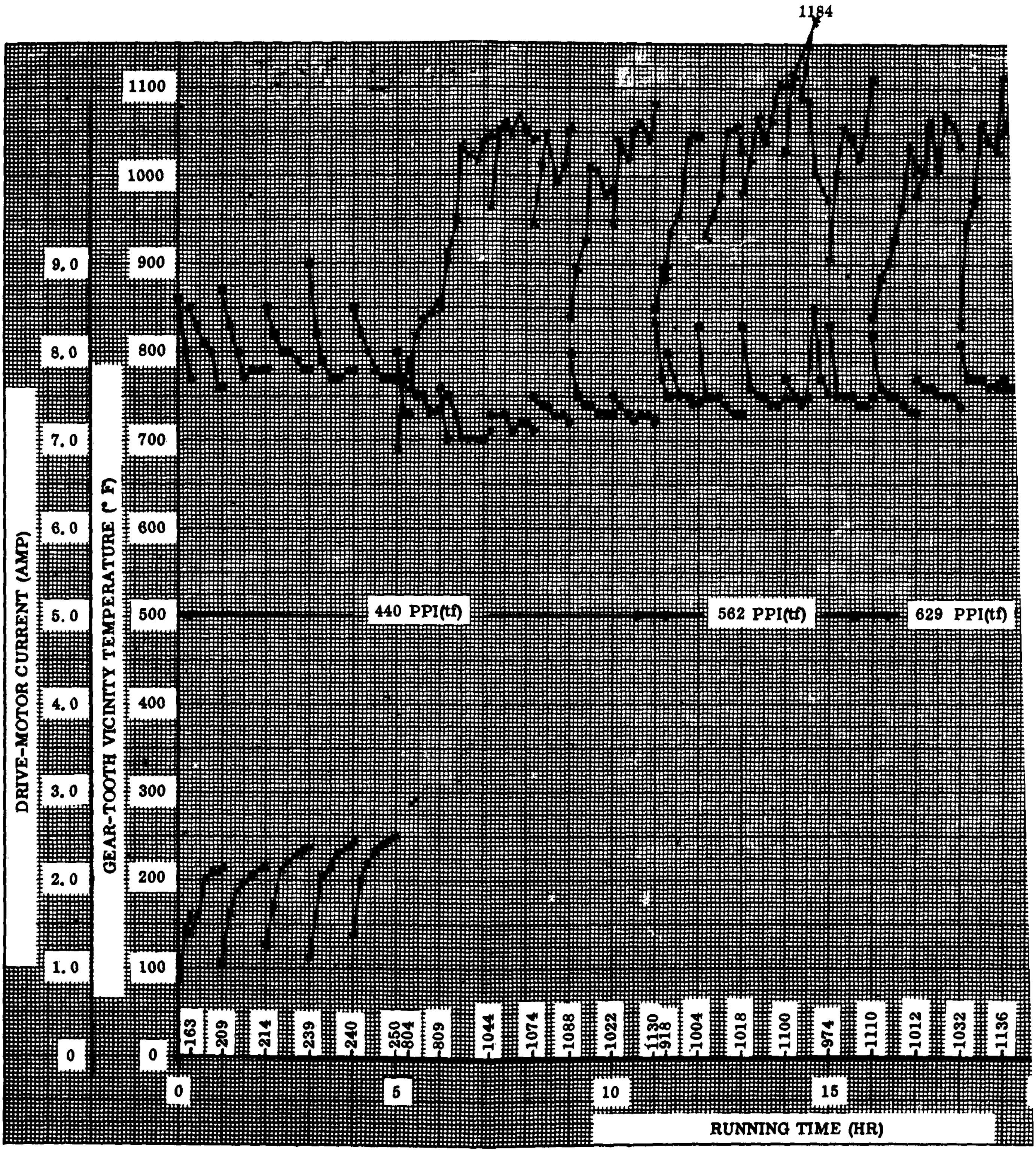
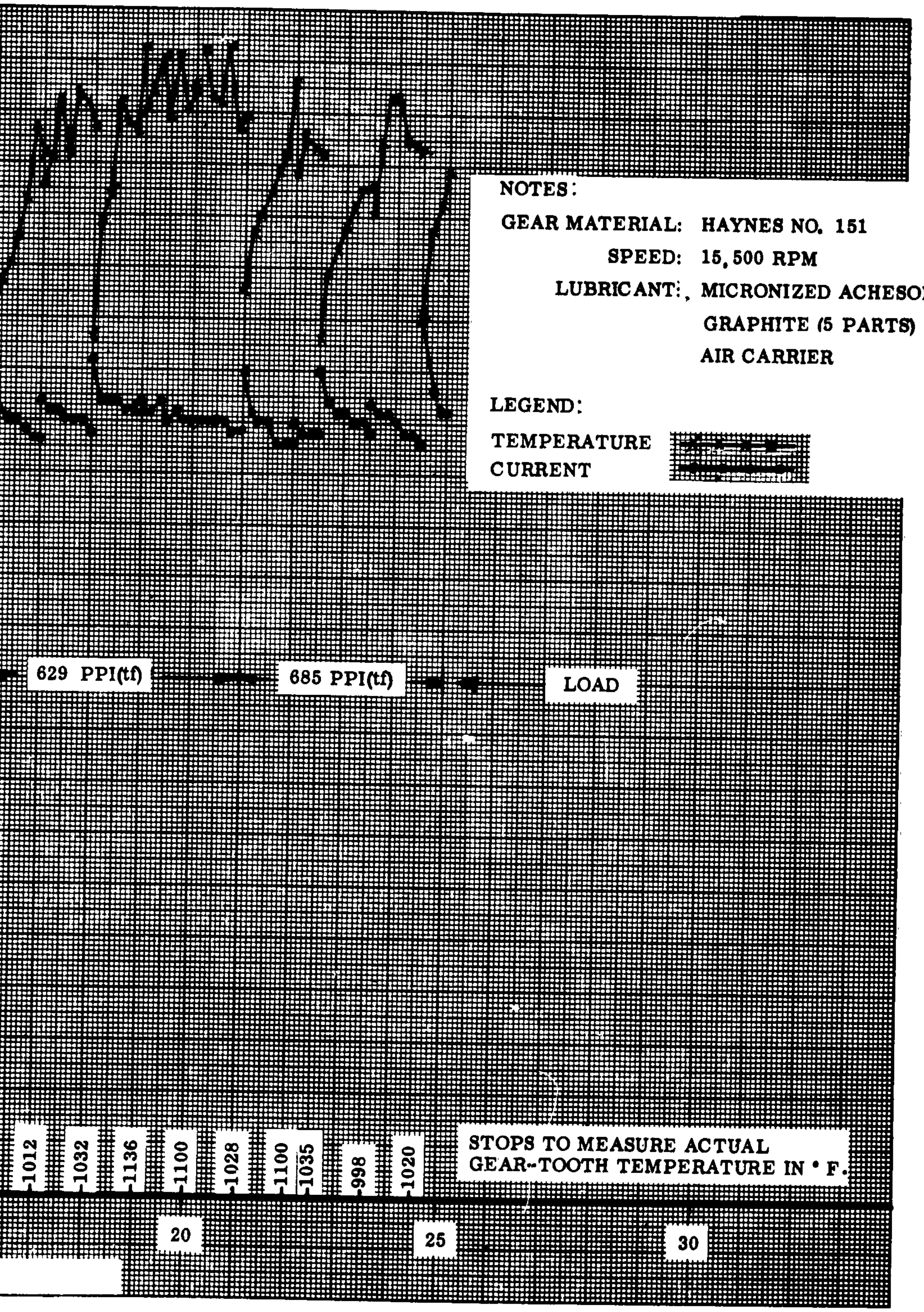


Figure 20. Test G-118 Performance Curve


NOTES:
GEAR MATERIAL: HAYNES NO. 151
SPEED: 15,500 RPM
LUBRICANT: MICRONIZED ACHESON NO. 38 GRAPHITE (5 PARTS) PLUS CdO (1 PART) IN AIR CARRIER
LEGEND:
TEMPERATURE
CURRENT
629 PPI(tf)
685 PPI(tf)
LOAD
1012
1032
1136
1100
1028
1100
1035
998
1020
STOPS TO MEASURE ACTUAL GEAR-TOOTH TEMPERATURE IN ° F.
20
25
30

2

wear appeared, although slight abrasions could be seen on the tooth tips. Measurements of the teeth filmed with lubricant indicated an average increase of 0.004 inch. The average lubricant flow rate during the test interval was 1.1 grams per minute. A Zyglo procedure revealed no fatigue cracks at the roots of the gear teeth.

The gears were tested again after 16 hours of operation. The black coating remained as before and the teeth continued to be well coated with lubricant. Gear measurements increased about 0.001 inch at tooth locations where the lubricant coating remained undisturbed while the measurements increased from 0.002 to 0.004 inch at the locations where the lubricant coating had been removed. Measurements following removal of the lubricant coating revealed no measurable wear on the gear teeth, although abrasions were visible. The lubricant continued to flow at the average rate of 1.1 grams per minute during this 7-hour test interval.

It was noted that operation continued to be smooth after four additional hours of testing. The rate of lubricant flow remained at 1.1 grams per minute during this period. Tooth-tip and pitch-line measurements indicated increases across each gear from 0.0022 to 0.0100 inch. Lubricant film was removed where the greatest amount of buildup had occurred. Further measurements at these points indicated that no wear had occurred. A repetition of the Zyglo procedure revealed no cracks at the roots of the gear teeth.

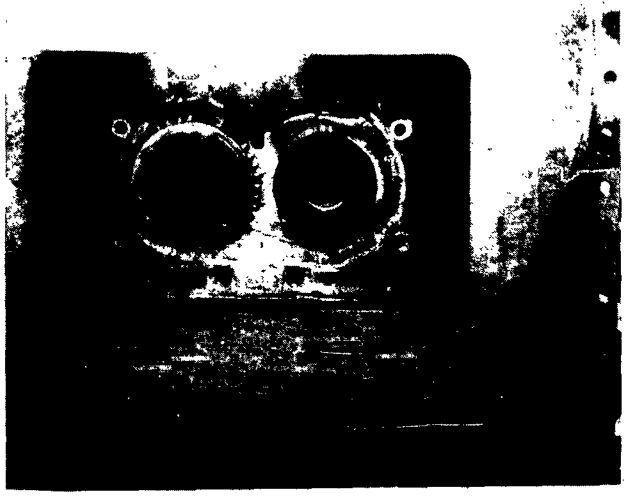
All factors checked in previous inspections remained the same after 24-1/2 hours of testing under conditions which were not changed. It was considered appropriate as the testing continued to determine if the increase in measurements across the gears would vary if the supply of lubricant to the gears were discontinued for short intervals. A 1 hour 10 minute run was conducted to recoat the areas of the gear teeth from which lubricant had been removed for wear measurements. When the lubricant supply was shut off, only about 30 seconds elapsed before a rapid increase in the power requirement required the cessation of the test. The gears were removed from the test rig and inspected. The brightly polished tooth flanks were lightly filmed with lubricant. Abrasions were found on the tips of the teeth when the film was removed. The hard black coating on the noncontacting surfaces had continued to adhere. Measurements across each gear increased in only five of 20 locations. Measurements at the other locations indicated a decrease ranging from 0.001 to 0.006 inch. It appears that the wearing away of the lubricant coating is accompanied by severe friction.

Testing was resumed with an increase in the load imposed on the gears to 685 ppi(tf). The gears failed with a shearing of teeth and the right-hand shaft was rended as shown in Figure 21 in a violent interruption of the testing after 2-1/2 hours. Test G-120 ran for a total of 28 hours and 10 minutes. Figure 22 is the performance curve of test G-120.

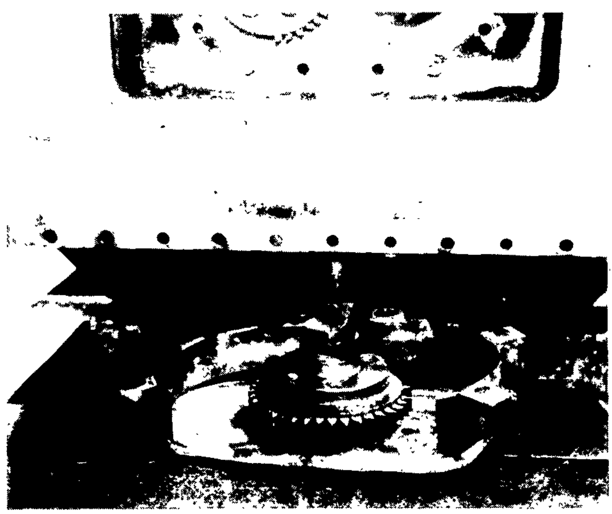
Stresses were calculated at the conclusion of test G-120 indicating that the shaft failure might have been caused by a bending stress induced by the reduction of backlash in the gear resulting form a buildup of lubricant film on the teeth.

Rene' 41 Gear Tests

Test G-121 consisted of testing spur gears of two different materials. One gear was nickel-base superalloy (Rene' 41) and the other was cobalt-base superalloy (Haynes Alloy No. 151). Speed was constant during the test at 15,550 rpm and temperature was increased after the fifth hour from ambient to about 900° F. The run continued for

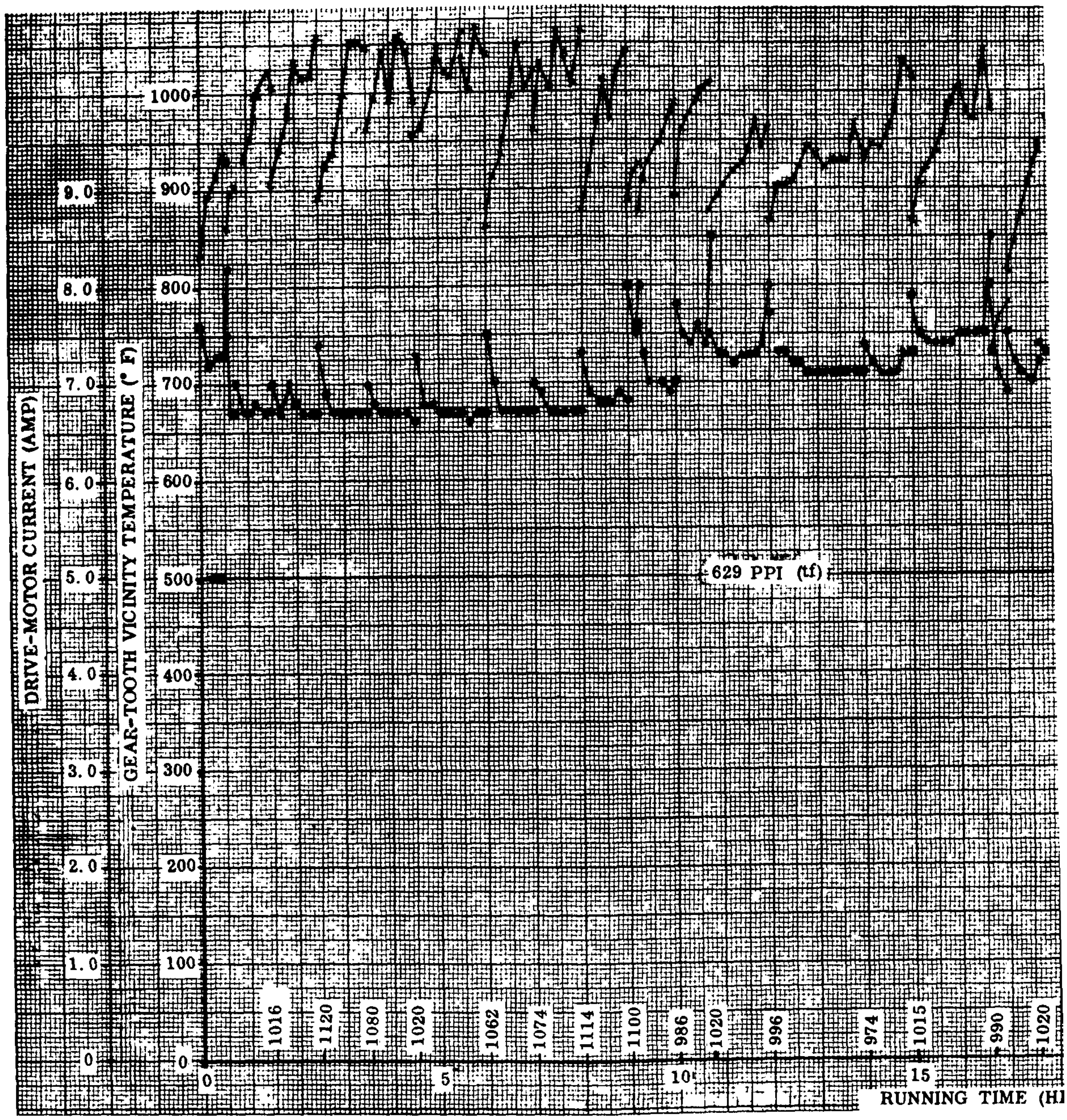


A. Damaged Test Gear and Broken Shaft



B. Damaged Test Gear Attached to Portion of Shaft

Figure 21. Gear and Rig Damaged in Test G-120


DRIVE-MOTOR CURRENT (AMP)
GEAR-TOOTH VICINITY TEMPERATURE (° F)
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
1000
900
800
700
600
500
400
300
200
100
0
629 PPI (tf)
1016
1120
1080
1020
1062
1074
1114
1100
986
1020
996
974
1015
990
1020
0
5
10
15
RUNNING TIME (H

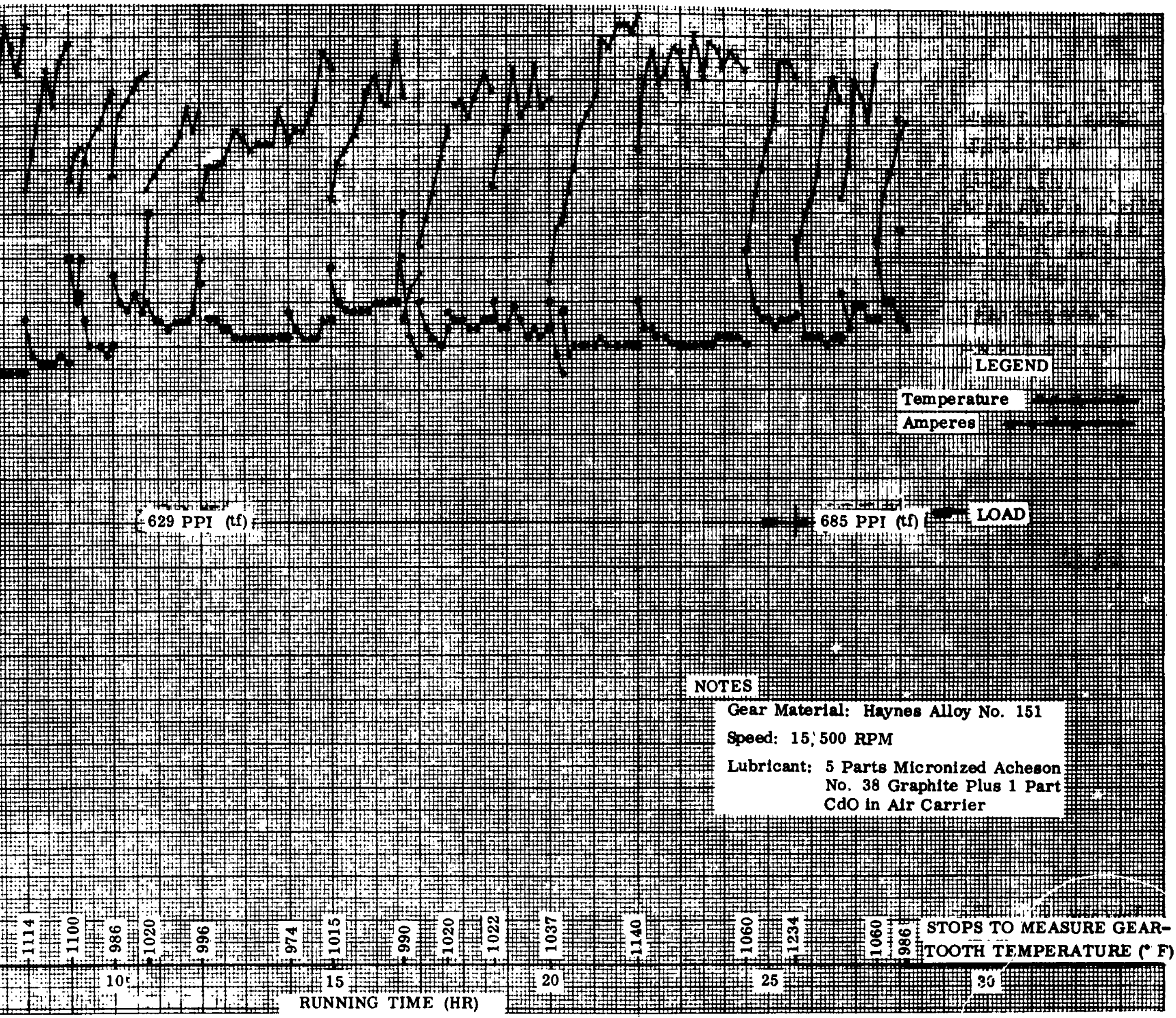


Figure 22. Test G-120 Performance Curve

about 15 hours when the cobalt-base superalloy gear failed together with the right-hand test rig shaft. The greatest load imposed during this test was 629 ppi(tf). It was observed during this test that a good film of lubricant coated the nickel-base superalloy gear whereas a thin patchy film was applied to the cobalt-base superalloy gear.

The gear tooth measurements of the Haynes No. 151 gear from test G-121 are shown in Table 7. It should be noted that the maximum wear occurs during the initial 5 hours of operation. The lubricant then seems to build up on the gear teeth and after 14 hours of operation the addendum measurement approaches the initial reading.

Test G-123 was conducted with the objective of evaluating gears of Rene' 41 when using powdered lubrication. The speed was set at 10, 350 rpm and the load at 440 ppi(tf). After 5 hours of operation at ambient temperature (98° F to 140° F), measurements indicated slight wear of teeth.

Operation through this period was smooth. The next 5 hours of operation was at a speed of 10, 350 rpm, a load of 440 ppi(tf) and an average gear-tooth temperature of 700° F. There was no appreciable change in gear tooth dimensions after this 5-hour run. The temperature was then increased to 900° F with no change in load or speed. After 5 hours at these conditions there was a slight increase in gear-tooth dimension due to lubricant buildup on teeth. The temperature was increased to the temperature range of 950 to 1000° F. After 4 hours and 10 minutes, the gear-rig motor current increased sharply and the gears became noisy. The test was stopped. The total operating time of test G-123 was 19 hours 10 minutes. The average lubricant flow rate through this test was 1.26 grams per minute. Figure 23 is the performance curve for test G-123.

After reviewing previous tests, it was noted that failures frequently occurred within the first quarter hour after startup. The rig is stopped every hour to check load and gear tooth temperature and then the rig is restarted. This would give evidence that the large shock applied to the gears by initial acceleration of the 5 horsepower gear rig motor might contribute to premature failure of gears. Follwing test G-123 the motor startup procedure was altered as described on page 7 to reduce the initial shock load.

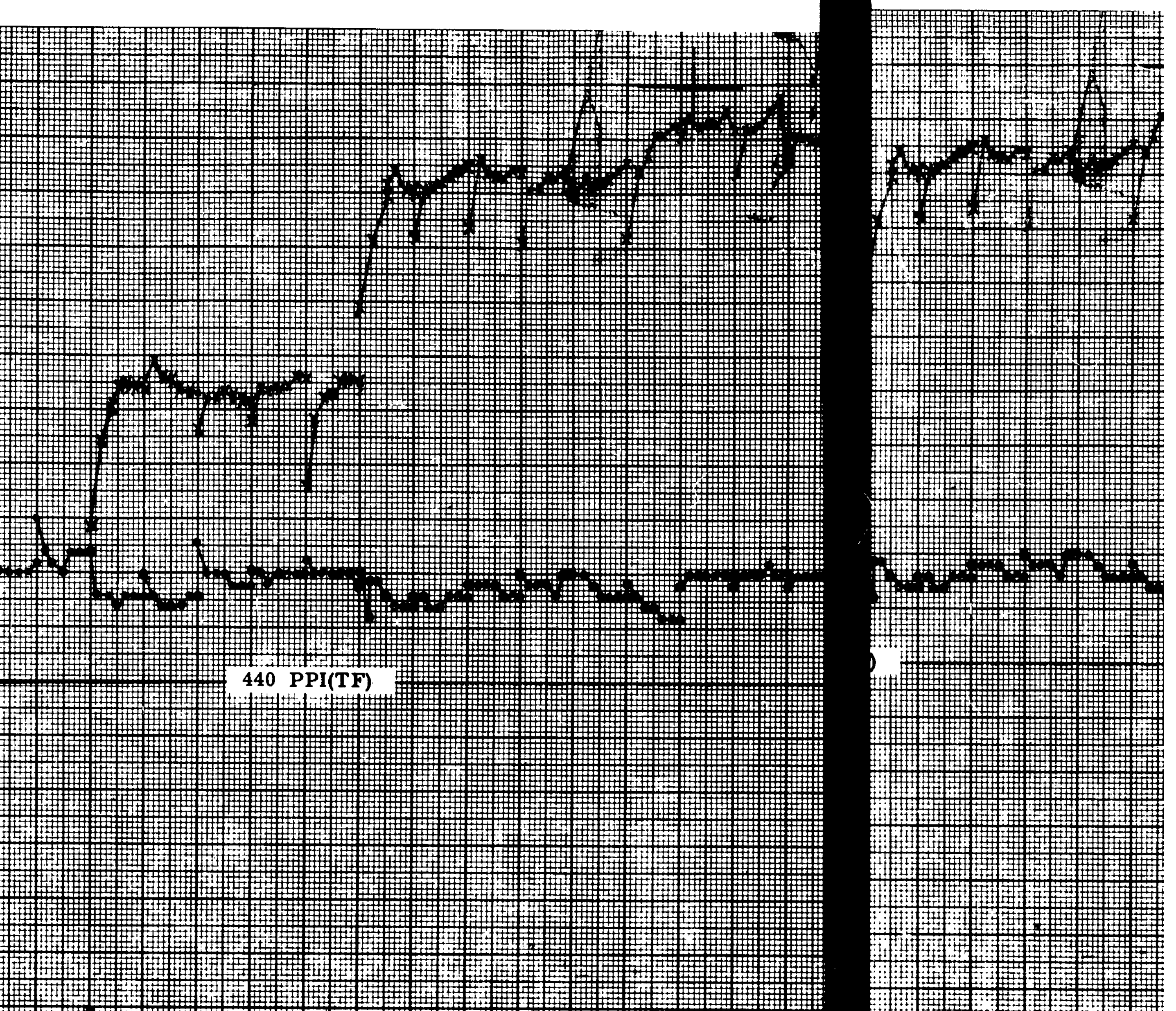
Haynes 6B Tests

Test G-124 was conducted to evaluate a gear set fabricated from Haynes Stellite No. 6B when using powdered lubrication. The speed was adjusted to 10, 350 rpm and the initial load was 440 ppi(tf). After 5 hours of ambient temperature testing (80° F to 175° F), measurements of the gear teeth indicated no change in size. The load was maintained at 440 ppi(tf) for the next 10 hours (4 hours at a temperature of 700° F and 5 hours at a temperature of 1000° F. Measuring the gear teeth after the 4 hours at 700° F showed no significant change in dimensions but after the 5 hours at 1000° F there was a slight increase in dimensions probably due to lubricant buildup.

For the next 5 hours the load was increased to 562 ppi(tf) while temperature and speed remained constant for the remainder of the test at 1000° F and 10, 350 rpm. The gear teeth exhibited a uniform film of lubricant and performance was smooth. The load was increased to 629 ppi(tf) for the next 5 hours, followed by 5 hours at 685 ppi(tf) 5 hours at 720 ppi(tf) and the last 15 hours at 1000 ppi(tf). After each 5-hour period, the gears were measured and the performance was adjudged to be good. The dimensions of the gear teeth increased slightly due to lubricant buildup, and after 49 hours had increased uniformity to a thickness of 0.002 inch. No signs of gear wear were apparent. At this point in the test program it was felt that more useful information could be obtained by temperature cycling the Haynes No. 6B gears in lieu of continuing testing at 1000° F.

TABLE 7. GEAR TOOTH MEASUREMENTS - HAYNES NO. 151 GEAR TEST G-121

	0.144 DIAMETER PIN MEASUREMENTS					0.210 DIAMETER PIN MEASUREMENTS				
Reading Number	Initial Reading	Final Reading (14 Hrs)	Total Change In. x 10^{-4}	Change After 9 Hours In. x 10^{-4}	Change After 5 Hours In. x 10^{-4}	Initial Reading	Final Reading (14 Hrs)	Total Change In. x 10^{-4}	Change After 9 Hours In. x 10^{-4}	Change After 5 Hours In. x 10^{-4}
1	3.4203	3.4200	- 3	-13	- 6	3.6449	3.6450	+ 1	- 1	- 4
2	3.4208	3.4199	- 9	-18	-13	3.6450	3.6450	0	- 1	- 8
3	3.4203	3.4200	- 3	-13	- 8	3.6450	3.6450	0	- 2	- 5
4	3.4204	3.4200	- 4	-14	-10	3.6450	3.6450	0	- 5	- 8
5	3.4202	3.4201	- 1	-12	-10	3.6450	3.6450	0	- 2	- 1
6	3.4204	3.4200	- 4	-14	-14	3.6450	3.6449	- 1	- 2	- 7
7	3.4200	3.4200	0	-10	- 8	3.6450	3.6449	- 1	- 5	- 5
8	3.4205	3.4200	- 5	-15	-15	3.6450	3.6450	0	- 4	- 4
9	3.4200	3.4200	0	-10	- 7	3.6450	3.6450	0	- 2	- 2
10	3.4206	3.4200	- 6	-16	-14	3.6450	3.6450	0	- 3	- 3
11	3.4209	3.4200	- 9	-19	-17	3.6450	3.6451	+ 1	- 5	- 6
12	3.4210	3.4200	-10	-20	-17	3.6450	3.6450	0	- 9	- 2
13	3.4209	3.4200	- 9	-18	-15	3.6450	3.6450	0	- 1	- 3
14	3.4205	3.4200	- 5	-15	-13	3.6450	3.6450	0	- 2	- 4
15	3.4203	3.4200	- 3	-13	-12	3.6450	3.6450	0	- 2	- 4
16	3.4210	3.4200	-10	-20	-19	3.6450	3.6449	- 1	- 1	- 2
17	3.4209	3.4200	- 9	-19	-17	3.6449	3.6450	+ 1	- 1	0
18	3.4205	3.4200	- 5	-15	-14	3.6449	3.6450	+ 1	- 3	- 1
19	3.4209	3.4200	- 9	-19	-18	3.6450	3.6450	0	+ 6	- 3
20	3.4208	3.4200	- 8	-18	-17	3.6450	3.6450	0	- 2	- 3
21	3.4206	3.4200	- 6	-16	-15	3.6450	3.6450	0	- 5	- 3
22	3.4205	3.4200	- 5	-15	-15	3.6450	3.6450	0	- 5	- 5
23	3.4205	3.4200	- 5	-15	-14	3.6450	3.6450	0	- 2	- 5
24	3.4209	3.4200	- 9	-15	-18	3.6449	3.6450	+ 1	- 1	- 3
25	3.4205	3.4200	- 5	-15	-13	3.6448	3.6450	+ 2	- 1	- 6
26	3.4209	3.4200	- 9	-15	-18	3.6450	3.6450	0	- 5	- 5
27	3.4210	3.4200	-10	-20	-19	3.6450	3.6450	0	0	- 4
28	3.4210	3.4200	-10	-19	-20	3.6450	3.6450	0	- 2	- 6
29	3.4210	3.4200	-10	-19	-18	3.6450	3.6450	0	0	- 2
30	3.4210	3.4200	-10	-19	-18	3.6450	3.6450	0	- 2	- 3
31	3.4210	3.4200	-10	-19	-18	3.6450	3.6450	0	- 2	- 5
32	3.4211	3.4200	-11	-22	-19	3.6450	3.6450	0	- 5	- 3
33	3.4211	3.4200	-11	-22	-21	3.6458	3.6449	- 9	-10	- 8
34	3.4211	3.4200	-11	-19	-19	3.6462	3.6448	-14	-11	-11
35	3.4211	3.4200	-11	-19	-18	3.6462	3.6450	-12	-10	-12
36	3.4210	3.4200	-10	-20	-17	3.6450	3.6465	+15	- 5	0
37	3.4210	3.4200	-10	-20	-17	3.6450	3.6452	+ 2	- 5	- 2
38	3.4210	3.4200	-10	-18	-15	3.6450	3.6450	0	- 6	- 1
39	3.4202	3.4200	- 2	-11	-12	3.6450	3.6450	0	- 6	- 7
40	3.4202	3.4200	- 2	-12	-12	3.6450	3.6450	0	- 3	- 3



440 PPI(TF)
128
150
800
720
717
734
734
904
933
930
921
941
980
973
940
904
933
930
921
941
5
10
15
RUNNING TIME, HRS
15
RUNNING TIME,

Curve

The average lubricant flow rate during this test was 1. 34 grams per minute. Figure 24 is the performance curve for test G-124.

Test G-125

Test G-125 was conducted for the purpose of temperature cycling Haynes Stellite No. 6B gears when using powder lubrication. A complete temperature cycle consists of running the gears from room temperature to 1000° F and back to room temperature. Prior to temperature cycling, the gears were conditioned for 1 hour at temperatures from 700 to 900° F, at a load of 440 ppi(tf), and a speed of 10, 350 rpm. The load was increased to 1000 ppi(tf) for the temperature cycling phase of the test.

The gears failed 10 minutes after the start of the third cycle. Total running time was 7 hours and 10 minutes. The average lubricant flow rate during the test was 1. 44 grams per minute. Figure 25 is the performance curve for test G-125. When the gears were examined after failure it was noted that there was no lubricant coating on the teeth.

It is believed that the 1 hour of conditioning was insufficient to allow an adequate lubricant buildup on the gears. It is probable that if some lubricant did adhere to the gears, it was worn away when the gears were operated at low temperatures. When the cycle reached temperatures high enough to permit the lubricant to coat the gear teeth, it was believed that again the time provided by the cycle was insufficient for a satisfactory coating to be applied.

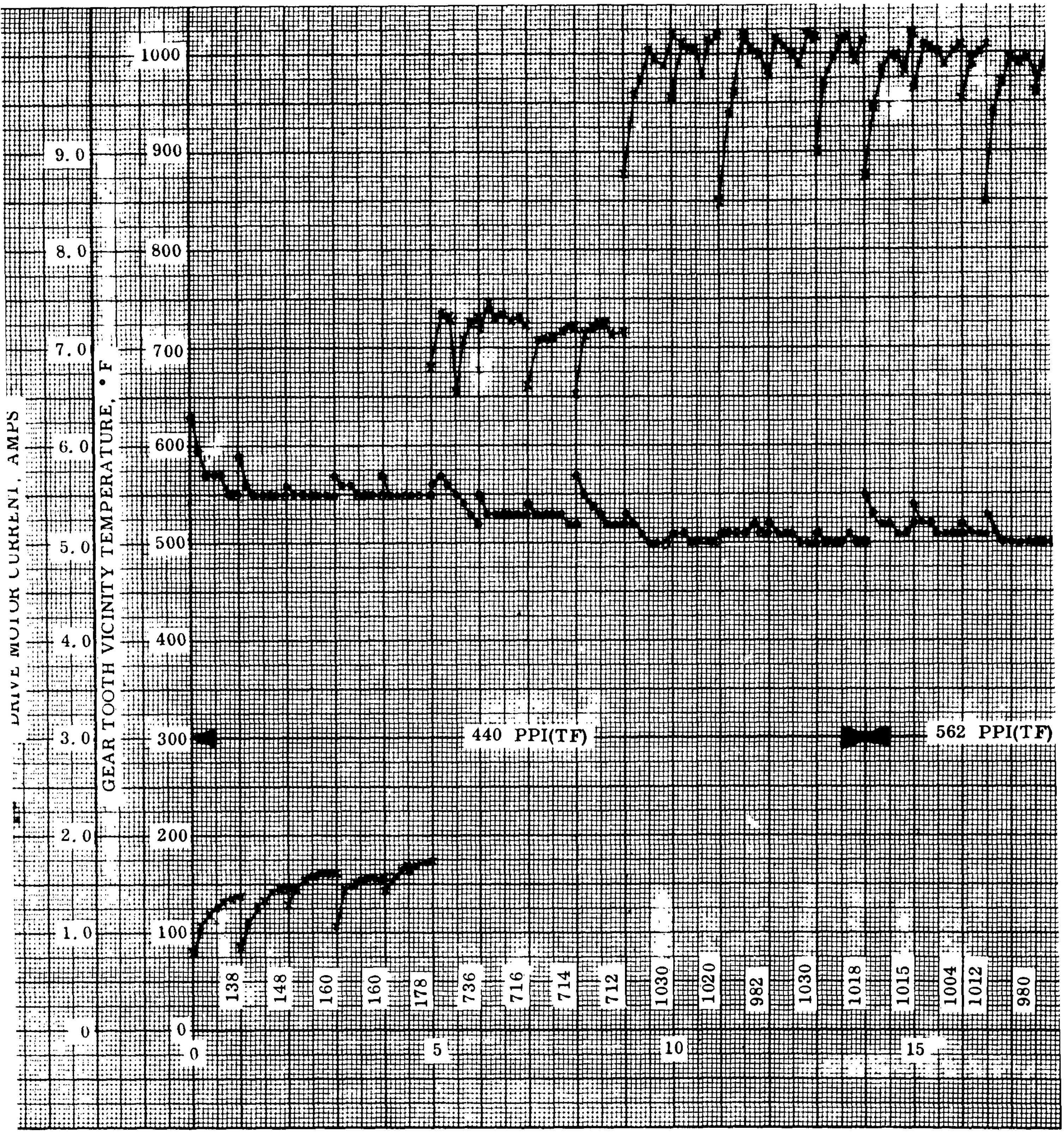
Test G-126

To remedy the light lubricant buildup that occurred in the previous test, test G-126 was conducted with a deliberate break in test continuity. The following intervals of operation were performed to condition the gears.

Time	Temperature	Load	Speed
2 hours	ambient	440 ppi (tf)	10, 350 rpm
2 hours	700° F	440 ppi (tf)	10, 350 rpm
2 hours	1000° F	440 ppi (tf)	10, 350 rpm
2 hours	1000° F	629 ppi (tf)	10, 350 rpm
2 hours	1000° F	1000 ppi (tf)	10, 350 rpm

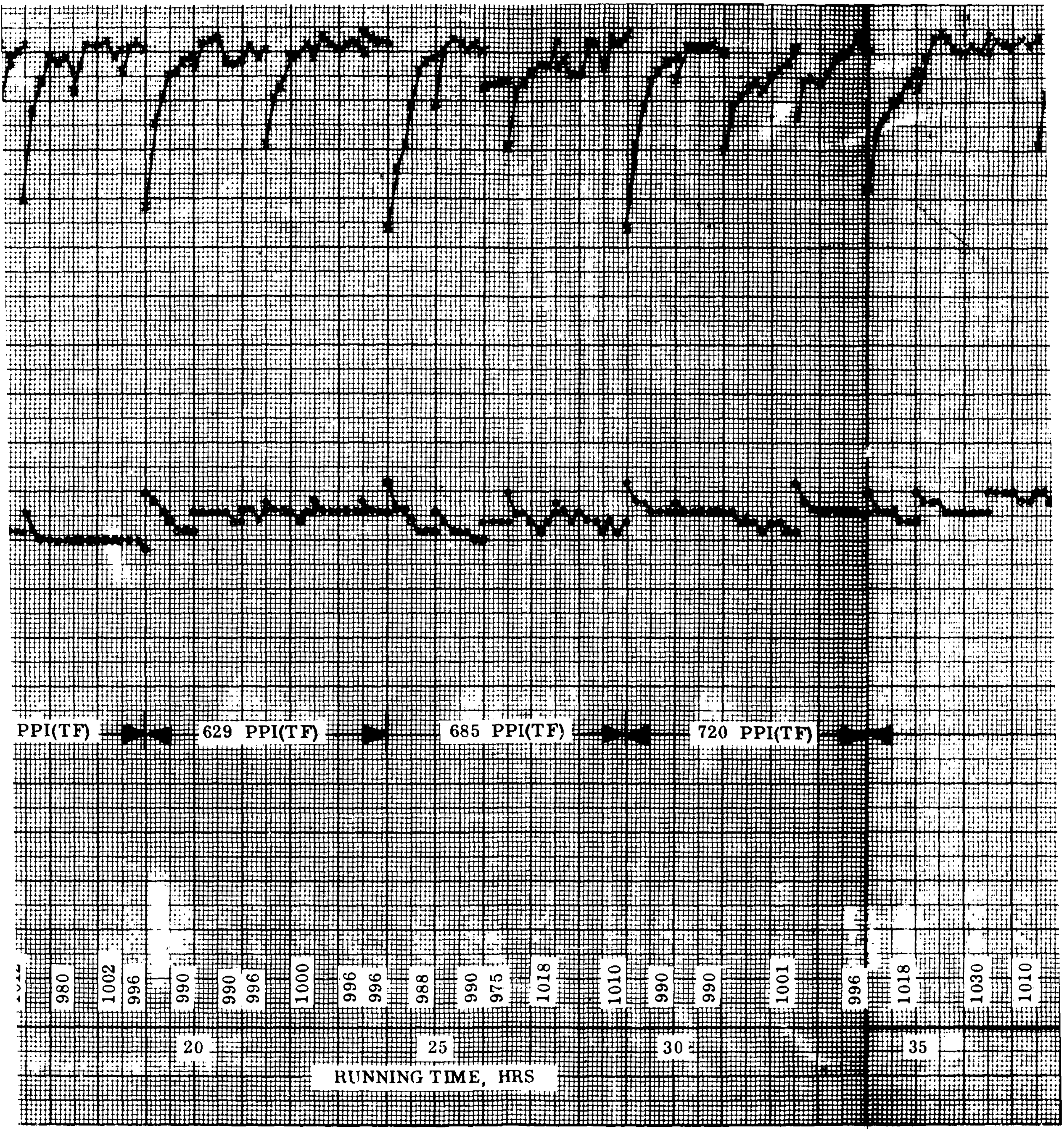
After the 10 hours of operation at the above conditions, the gears were inspected and measured. There was a slight increase in dimensions but the lubricant film appeared to be abraded. The gears were then operated for a total of 10 additional hours at a speed of 10, 350 rpm, a temperature of 1000° F and a load 1000 ppi(tf). During the first 5 hours at these conditions, the gears were measured and inspected and the lubricant coating was found to be inadequate. After the 20-hour breakin period, a lubricant coating of 0. 001 inch had formed on the gear surfaces and it appeared to have a uniform thickness.

The gears were cycled from room temperature to 1000° F and back to room temperature.



gure 24. Test G-124 Performance Curve

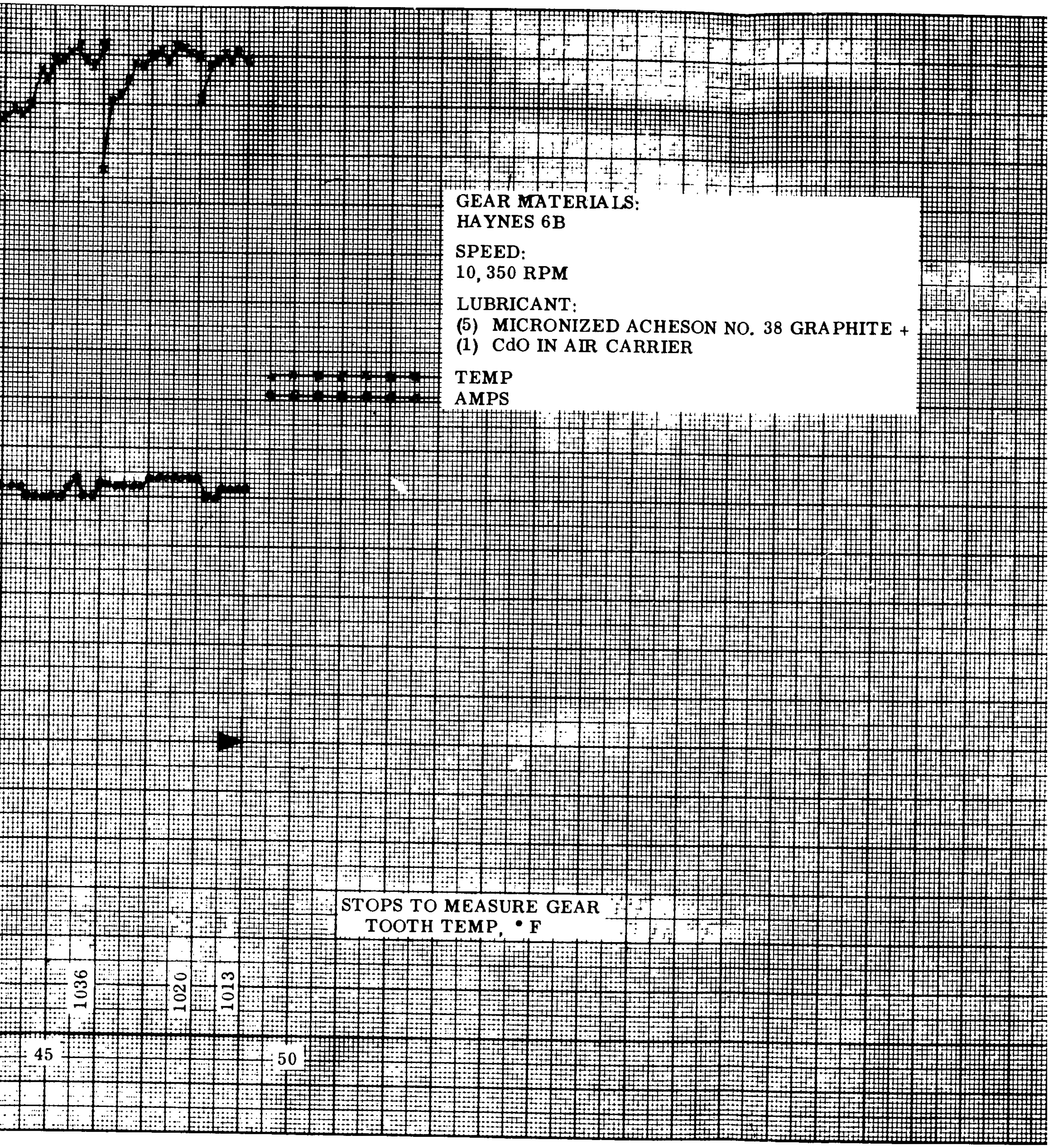
1


PPI(TF)
629 PPI(TF)
685 PPI(TF)
720 PPI(TF)
980
1002
996
990
990
996
1000
996
996
988
990
975
1018
1010
990
990
1001
996
1018
1030
1010
20
25
30
35
RUNNING TIME, HRS

2

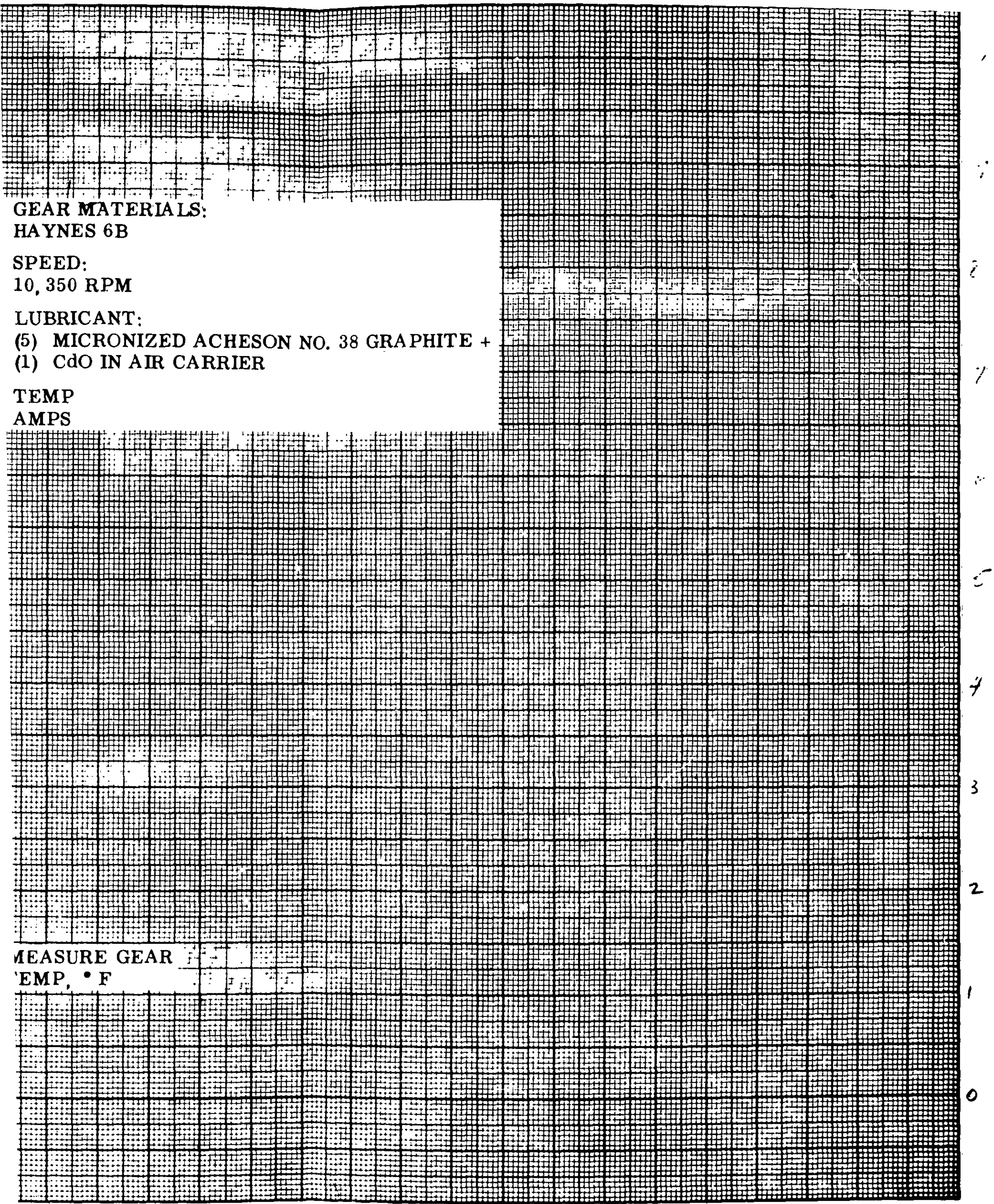

(TF)
1000 PPI(TF)
STOPS TO ME
TOOTH TEM
996
1018
1030
1010
1018
990
1018
1010
1008
1036
1020
1013
35
40
45
50

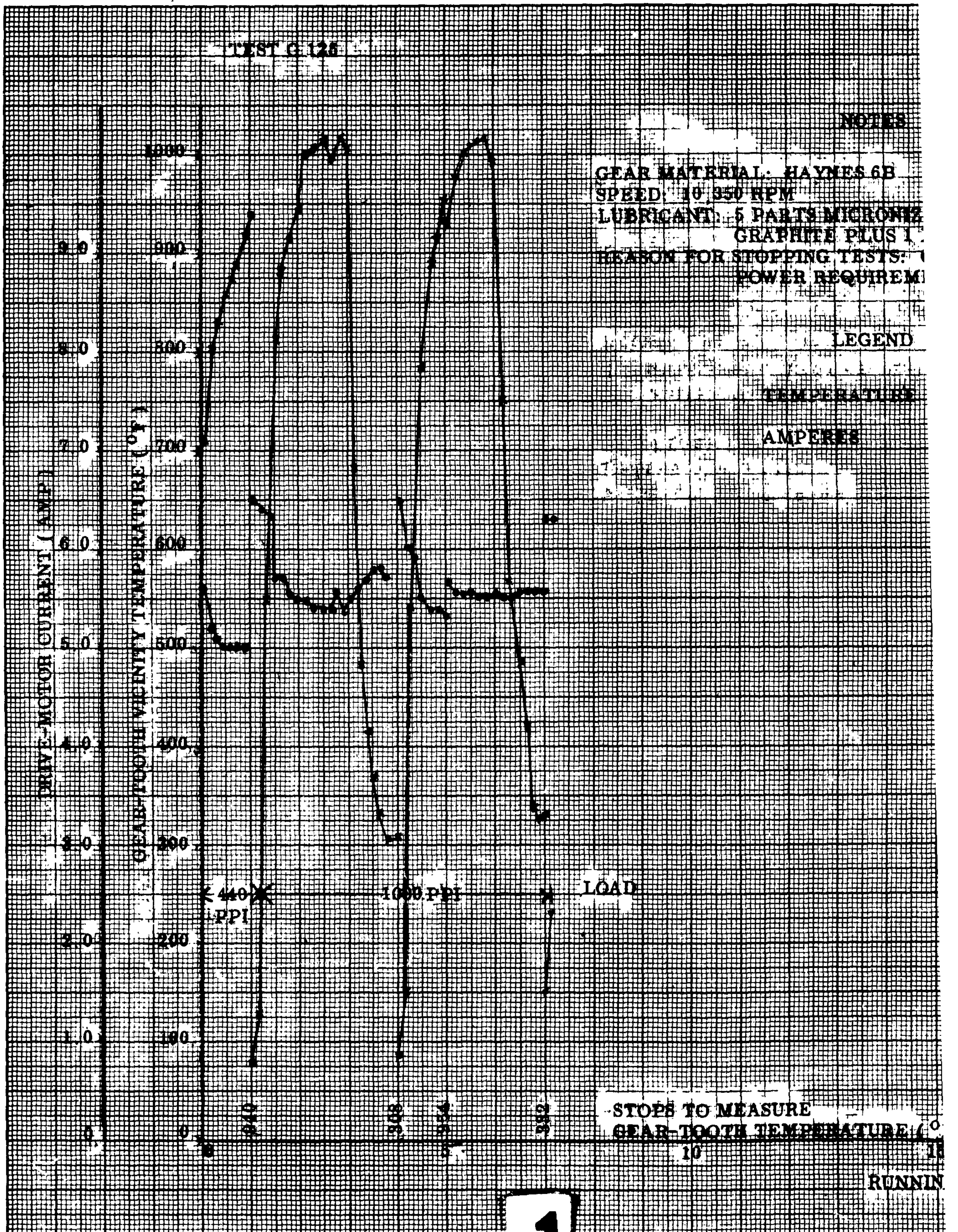
3



GEAR MATERIALS:
HAYNES 6B
SPEED:
10, 350 RPM
LUBRICANT:
(5) MICRONIZED ACHESON NO. 38 GRAPHITE +
(1) CdO IN AIR CARRIER
TEMP
AMPS
STOPS TO MEASURE GEAR TOOTH TEMP, °F
1036
1020
1013
45
50

4


GEAR MATERIALS:
HAYNES 6B
SPEED:
10, 350 RPM
LUBRICANT:
(5) MICRONIZED ACHESON NO. 38 GRAPHITE +
(1) CdO IN AIR CARRIER
TEMP
AMPS
MEASURE GEAR
TEMP, °F
7
5
4
3
2
1
0



TEST G-126
NOTES
GEAR MATERIAL: HAYNES 6B
SPEED: 10,350 RPM
LUBRICANT: 5 PARTS MICRONIZ
GRAPHITE PLUS 1
REASON FOR STOPPING TESTS:
POWER REQUIREM
LEGEND
TEMPERATURE
AMPERES
DRIVE-MOTOR CURRENT (AMP)
GEAR-TOOTH VICINITY TEMPERATURE (°F)
440 PPI
1000 PPI
LOAD
STOPS TO MEASURE
GEAR-TOOTH TEMPERATURE (°
RUNNIN

1

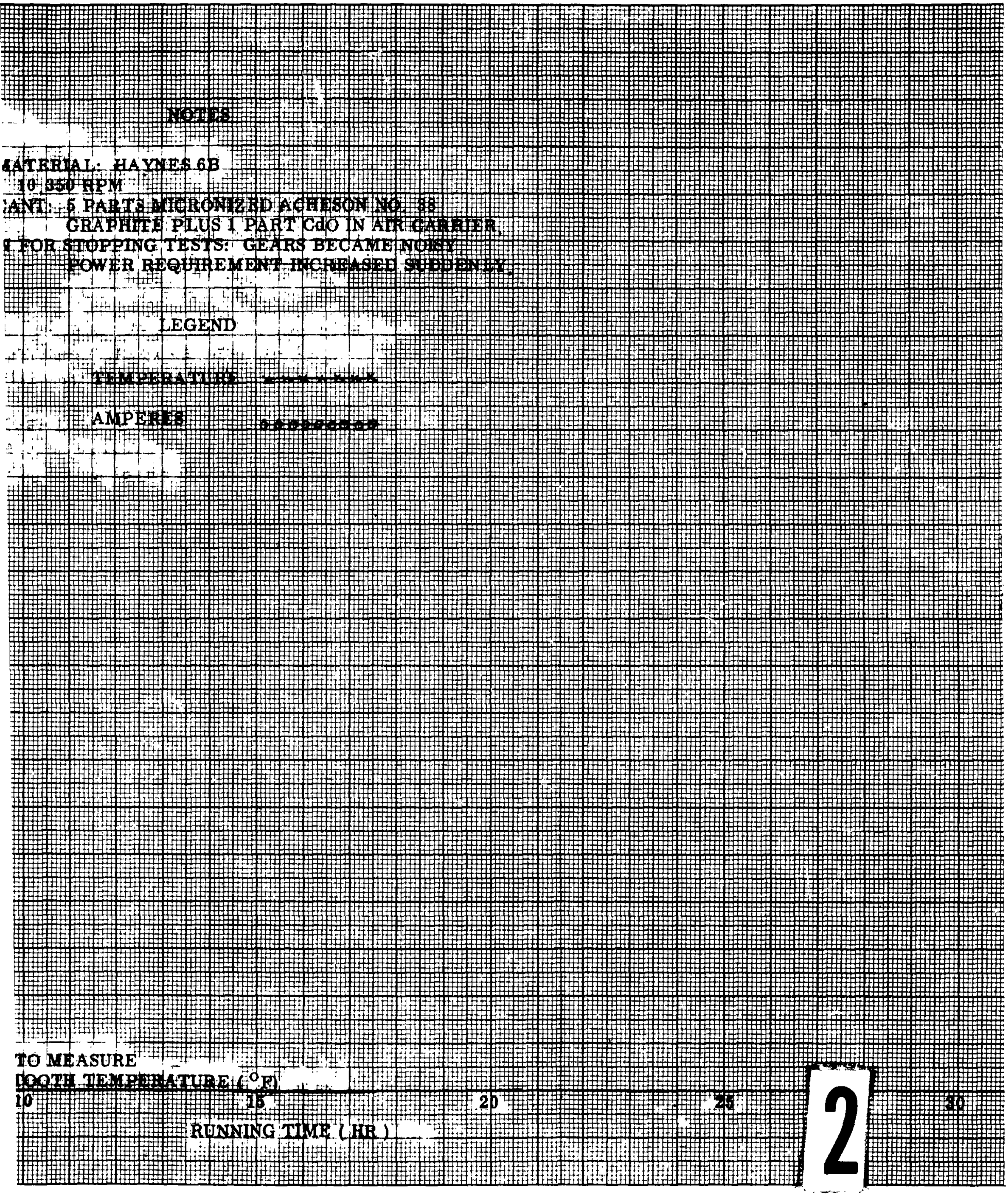


Figure 25. Test G-125 Performance Curve

After completing 10 full temperature cycles, the gears were stopped for the usual tooth-temperature and load checks. When the test was resumed, the rig motor current increased to 8.5 amps and was immediately shut down. Examination of the test rig revealed that an oil leak into the test head had caused the powder lubricant to cake and clog the lubricant inlet tube. The lubricant coating on the teeth had been abraded. Upon close examination of the gear teeth it was found that numerous teeth were cracked and most of the cracks were found at the tooth roots. Figure 26 shows a portion of gear G-126 enlarged to disclose the details of two cracks. It was interesting to note that most cracks appeared on the front face of the gear teeth. This would indicate that the gear tooth loading was uneven and that there was some misalignment in the rig that caused the load to be unevenly distributed across the gear teeth. No cracks continued from the front of a tooth to the back of a tooth.

This was the first time during the entire program that a gear test was stopped prior to an impending failure. The information gained by examining these gears indicates that the test conditions were not ideal and that under more uniform loading the life of these gears might have been extended. Although the average lubricant flow for the last 3 hours was 1.41 grams per minute, the interval during which the gears were running with the lubricant inlet tube clogged is unknown and the condition might have influenced a premature failure.

Figure 27 is the performance curve of test G-126.

The 20 hour run-in procedure attributed to achieving the 50-hour endurance run. The importance of the run-in is to provide a sufficient lubricant coating to enable the gears to survive the room temperature period of operation. The 20 hour length of time for run-in was established by running the gears until the teeth were completely covered with a film of lubricant.

Test G-127

The object of test G-127 was to evaluate the effect of shot peening Haynes No. 151 gears. Figure 28 is a shot-peended Haynes No. 151 gear. All previous failures of Haynes No. 151 gears occurred at the roots of the teeth. Since the roots are subjected to the greatest bending stress, it was decided to shot peen only the roots. The flanks would thus be unaltered and the contact surfaces of gears would remain unchanged.

The gears were operated for 4 hours at ambient temperature with the load at 440 ppi(tf) and the speed at 10, 350 rpm. Measurement of the gear teeth indicated wear of 0. 001 inch. Load was then increased to 562 ppi(tf) and the temperature was increased to 700° F. After 2 hours of operation at these conditions, the teeth failed.

After the failure of the gears, they were returned to the vendor for evaluation. They stated that the masking of the face of the teeth and shot peening only the root may create a problem between the work hardened root area and the soft nonwork hardened tooth area. As a suggestion for improving performance of remaining shot-peened gears, the vendor recommended that the gears should be shot peened over the entire tooth-face area as well as at the root. It was recommended that glass peening should follow shot peening to improve the gear surface finish.

The investigation of shot peening was not continued since it was out of the scope of this program. The Haynes Alloy No. 151 was ruled out of subsequent tests due to the fact that it is a cast material and had performed poorly in tests that had been run.

SPECIAL TESTS

Oven Tests of Lubricant

The objective of high-temperature testing the lubricant components and mixture in an oven was to determine the effect that elevated temperatures and various intervals of exposure would have on the graphite, cadmium oxide, and mixtures of different proportions of the two. The tests were conducted to generate quantitative data under simulated gear-test environments.

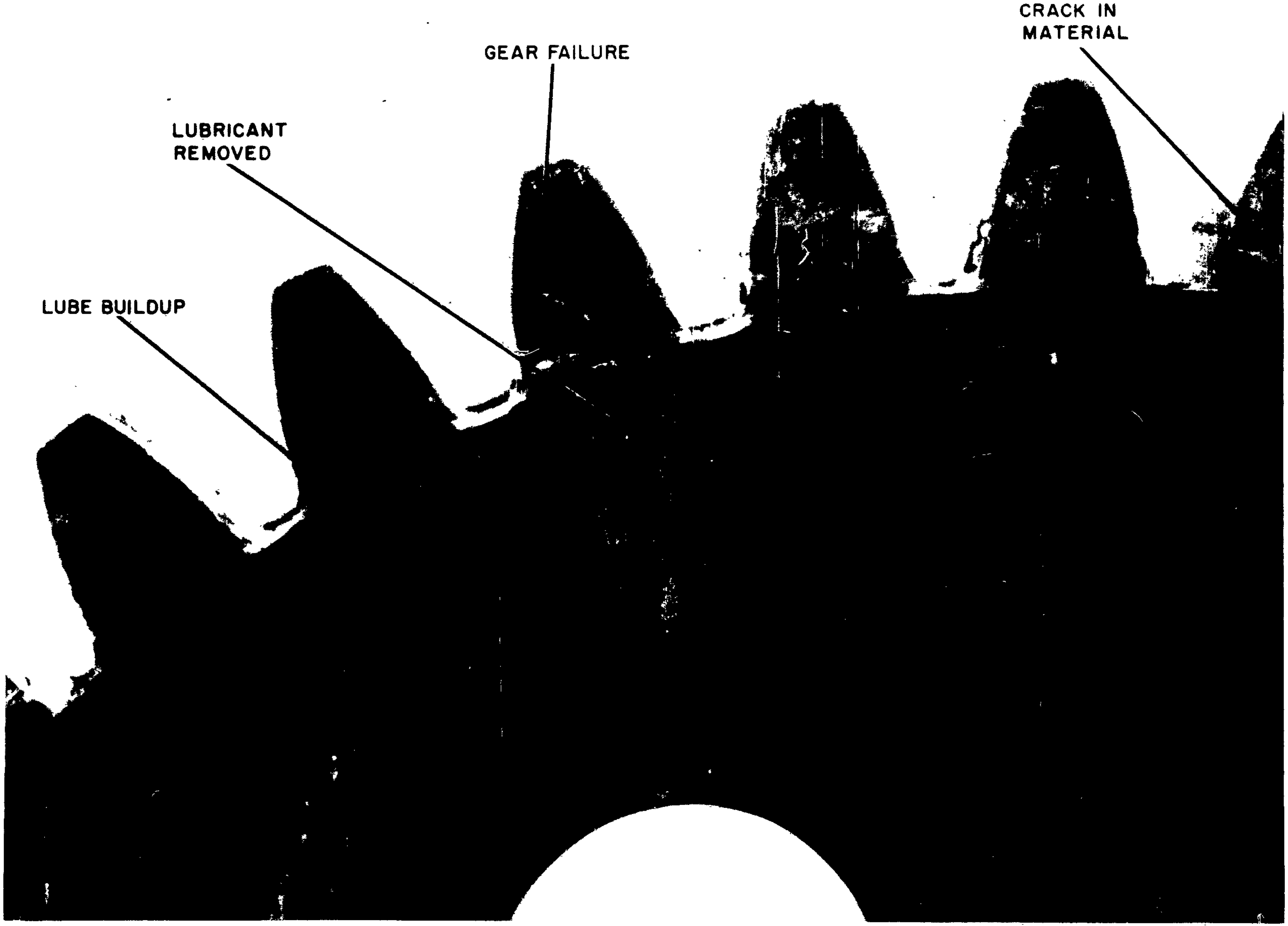


Figure 26. Gear G-126 Failure

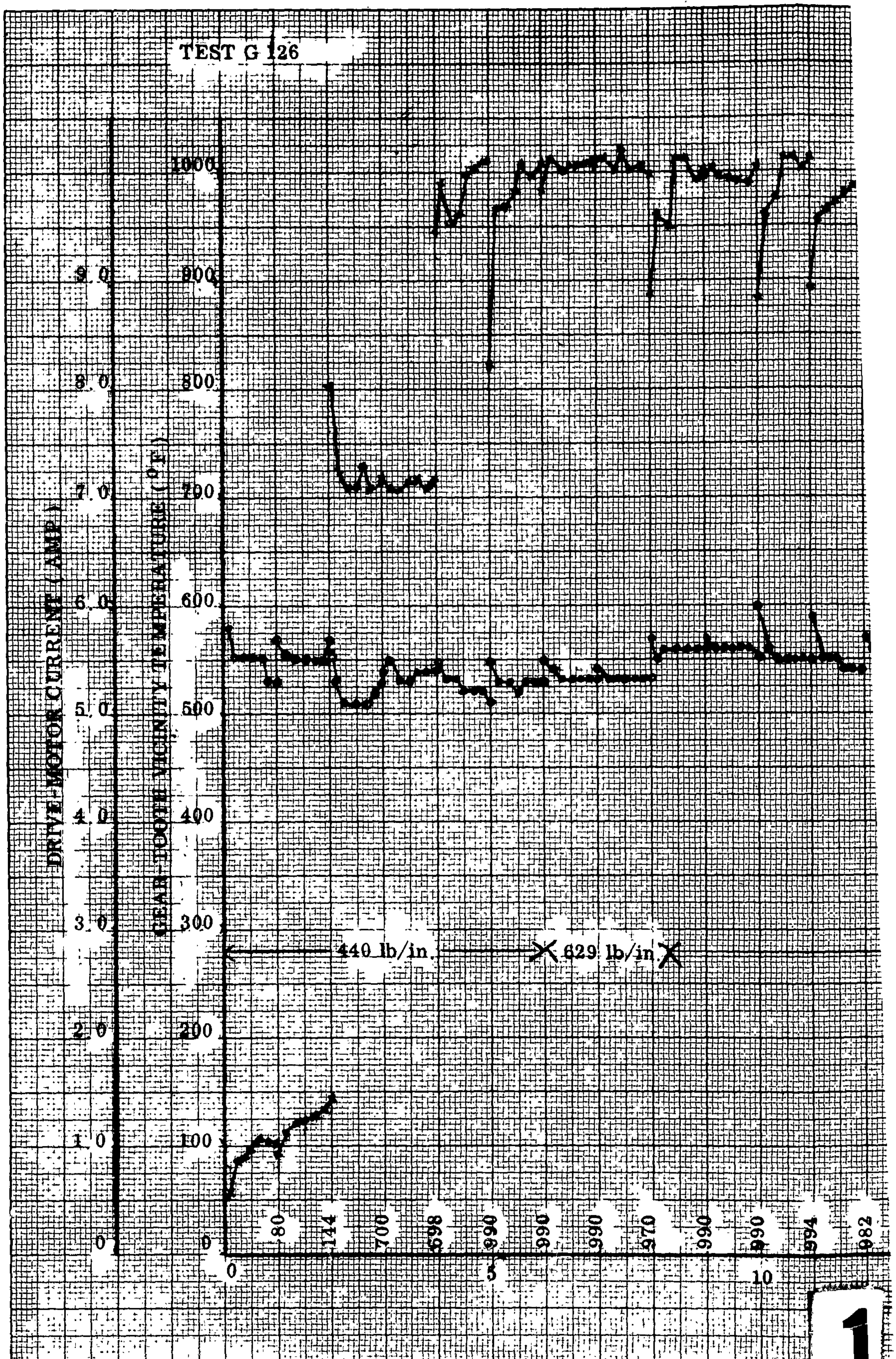
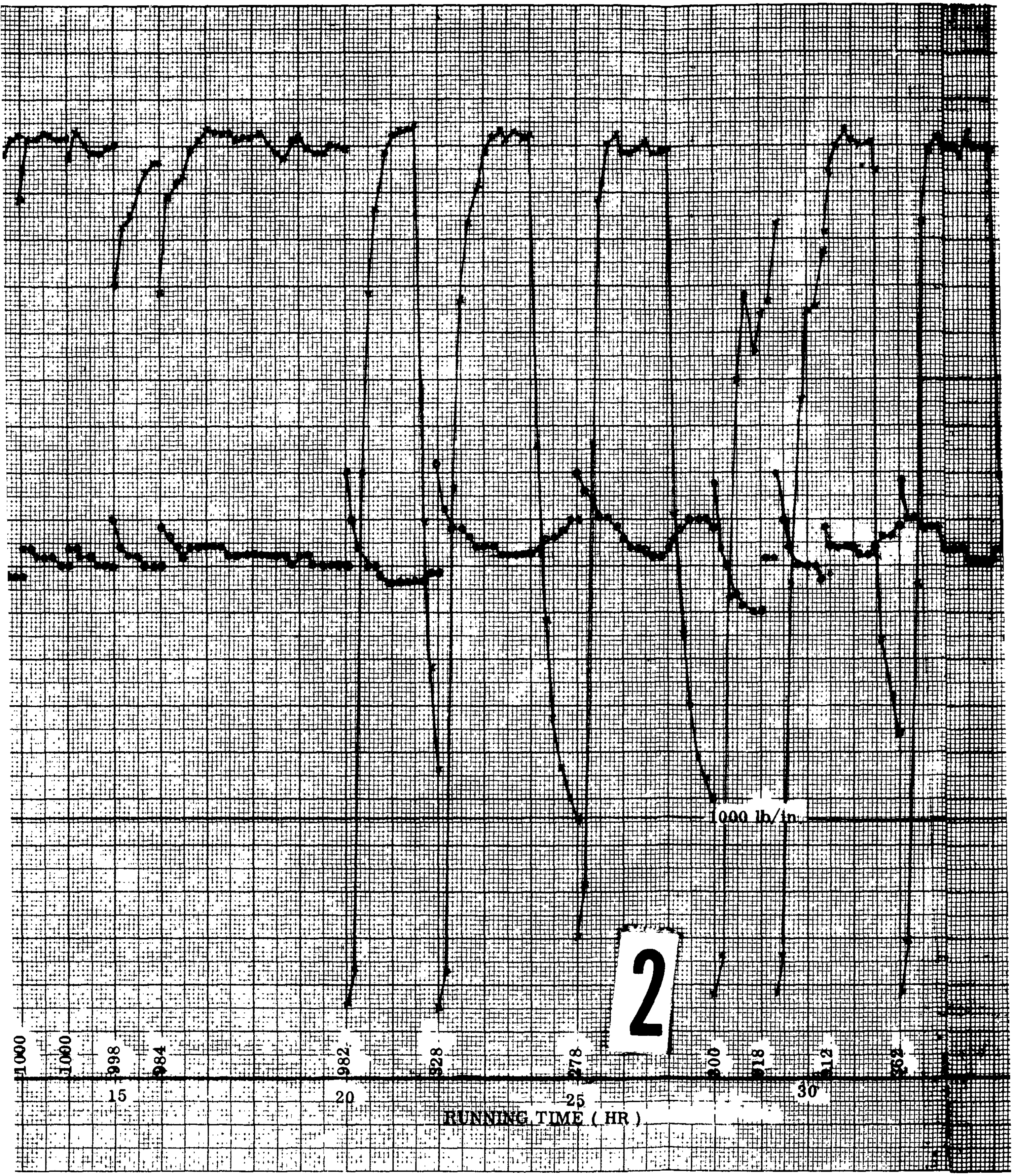
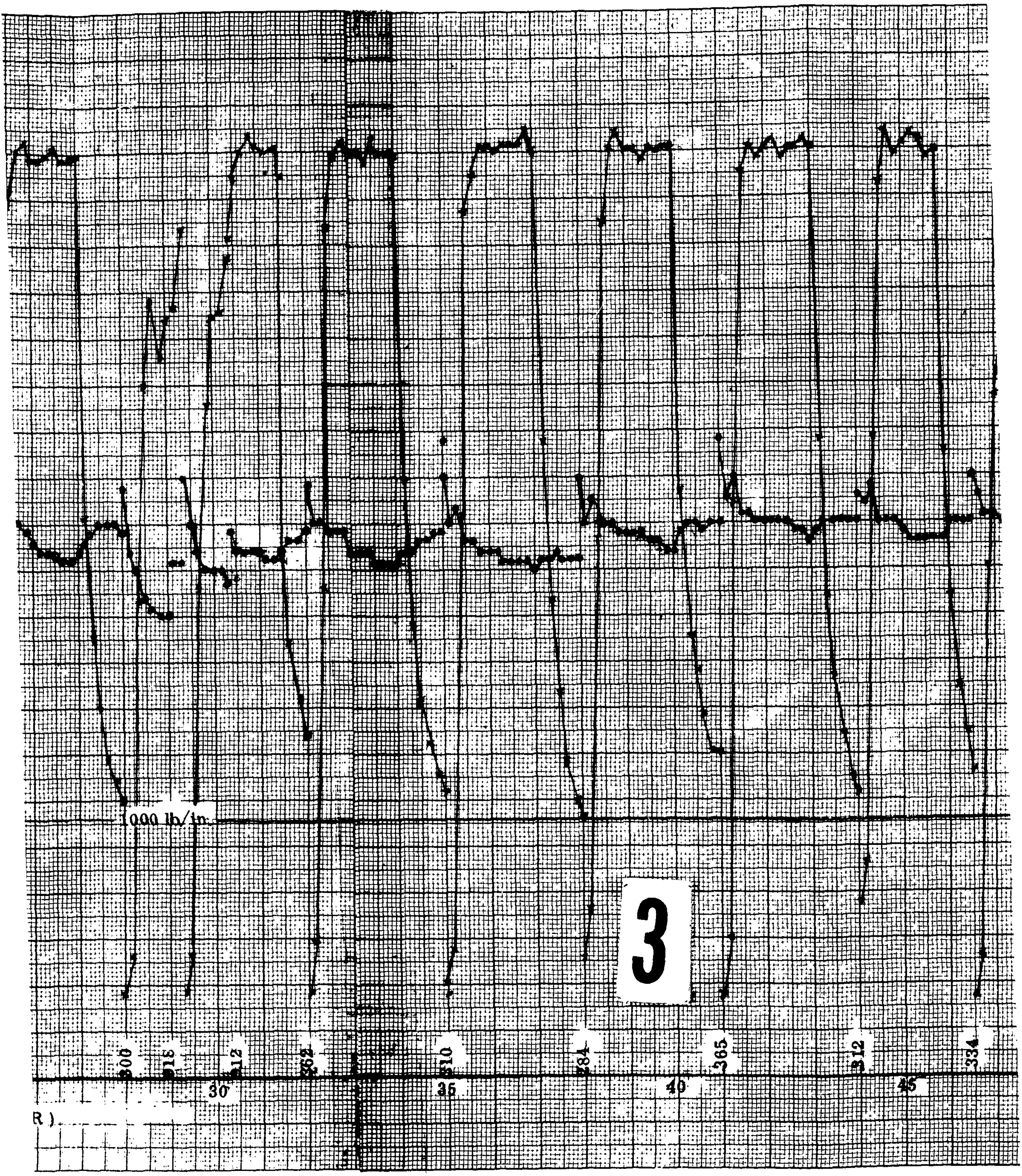
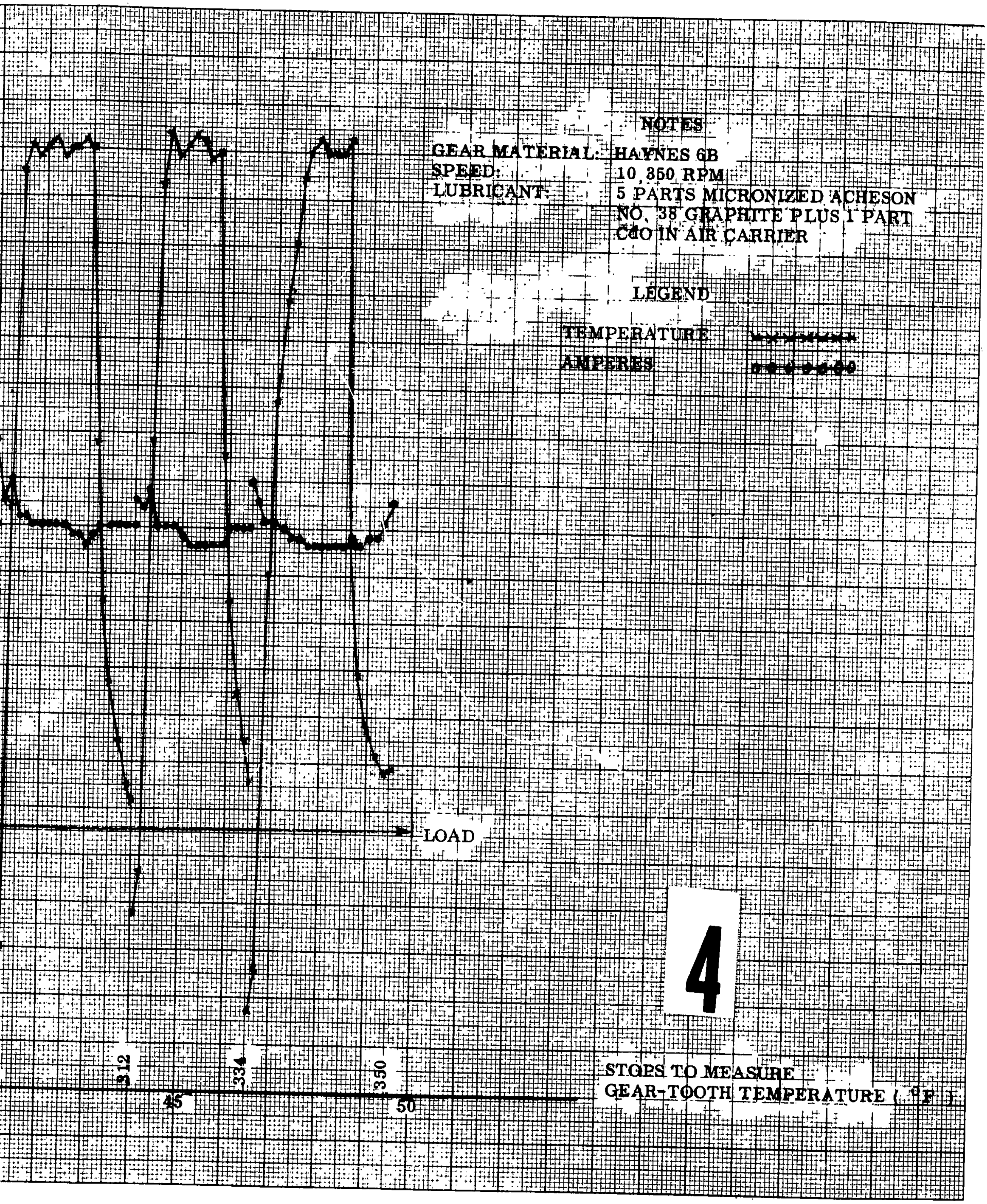


Figure 27. Test G-126 Performance Curve 72



1000 lb/in.
1000
1000
998
984
982
328
278
300
318
312
262
15
20
25
30
RUNNING TIME (HR)
2


1000 lb/in.
300
318
312
362
310
384
365
312
334
30
35
40
45
R)
3


NOTES
GEAR MATERIAL: HAYNES 6B
SPEED: 10,350 RPM
LUBRICANT: 5 PARTS MICRONIZED ACHESON NO. 38 GRAPHITE PLUS 1 PART CdO IN AIR CARRIER
LEGEND
TEMPERATURE
AMPERES
LOAD
4
312
334
350
45
50
STOPS TO MEASURE GEAR-TOOTH TEMPERATURE (°F)

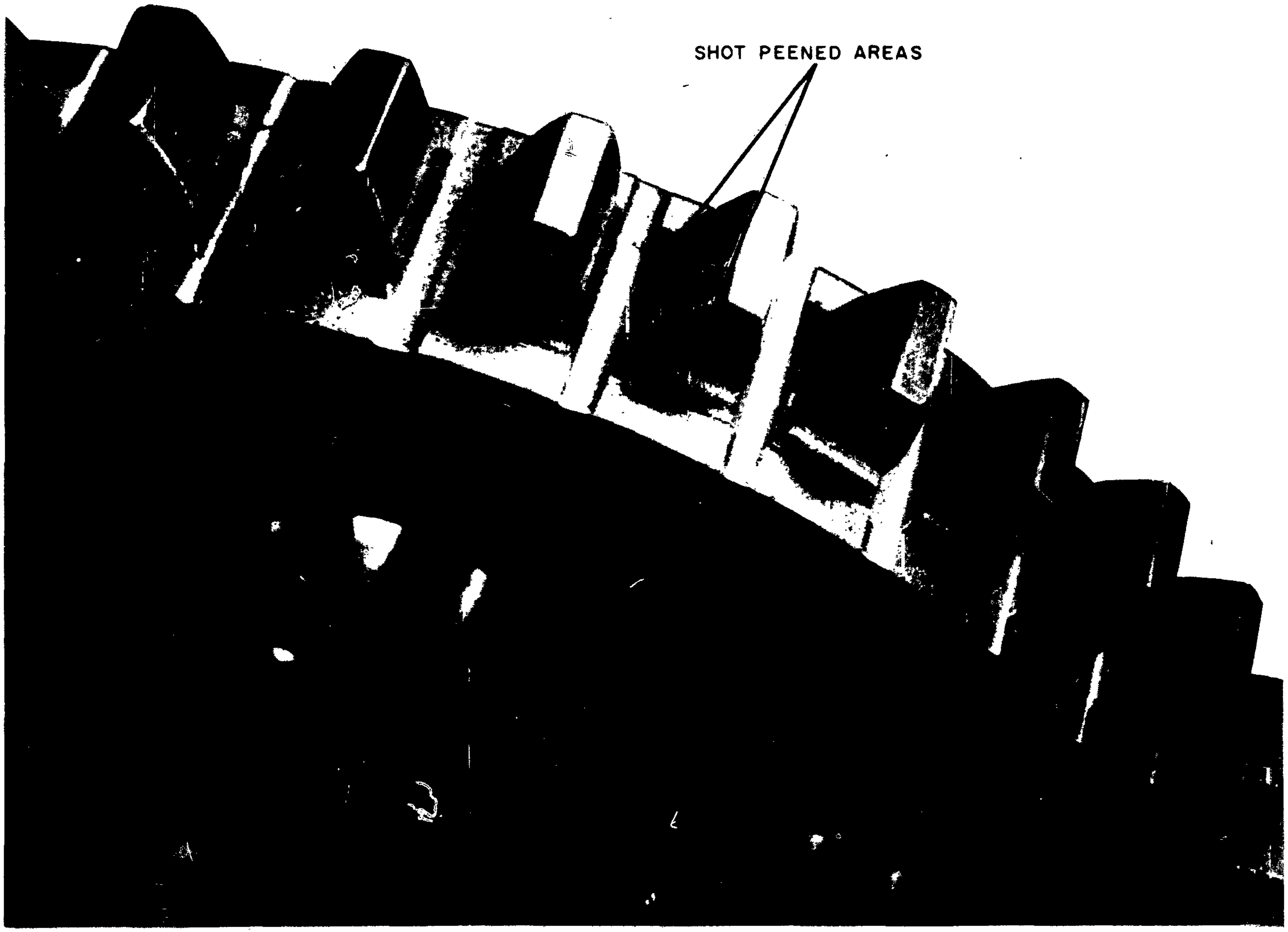


Figure 28. Shot-Peened Gear

The following procedure was used to determine the effect of varying temp
on the lubricant.

1. One-gram samples of the following were prepared.

   a. Cadmium oxide

   b. Mixture of 5 parts graphite to 1 part cadmium oxide

   c. Micronized Acheson No. 38 graphite

   d. Mixture of 4 parts graphite to 1 part cadmium oxide

2. Samples placed in porcelain beakers.

3. Samples subjected to temperature of 900° F for 5 minutes in oven.

4. Beakers removed from oven. Weights of sample residues measured
corded.

5. Steps 1, 2, and 4, repeated using fresh samples at temperatures of 9
1050, 1150, and 1200° F.

The following procedure was used to determine the effect of various expo
on the lubricant.

1. Four 1-gram samples of 5-to-1 mixture of graphite and cadmium oxi
pared.

2. Samples placed in porcelain beakers in oven at 1100° F.

3. One sample removed from oven after each 15-minute interval for 1 h

4. Weight of sample residue measured and recorded.

The results of the oven tests are shown in Figures 29 and 30. The 5-min
ing shown in Figure 30 was obtained from the corresponding reading shown in
for 1100° F using the 5-to-1 mixture.

The 5-minute interval was chosen to be the constant exposure time becau
lubricant used in the gear tests would not be subjected to elevated temperatur
longer intervals.

The test in which the interval of exposure was varied was performed to d
if it were practicable to collect and reuse the lubricant. The test would provi
mation about chemical or physical changes.

The 4-to-1 mixture was tested primarily to determine if the mixture rati
a critical parameter.

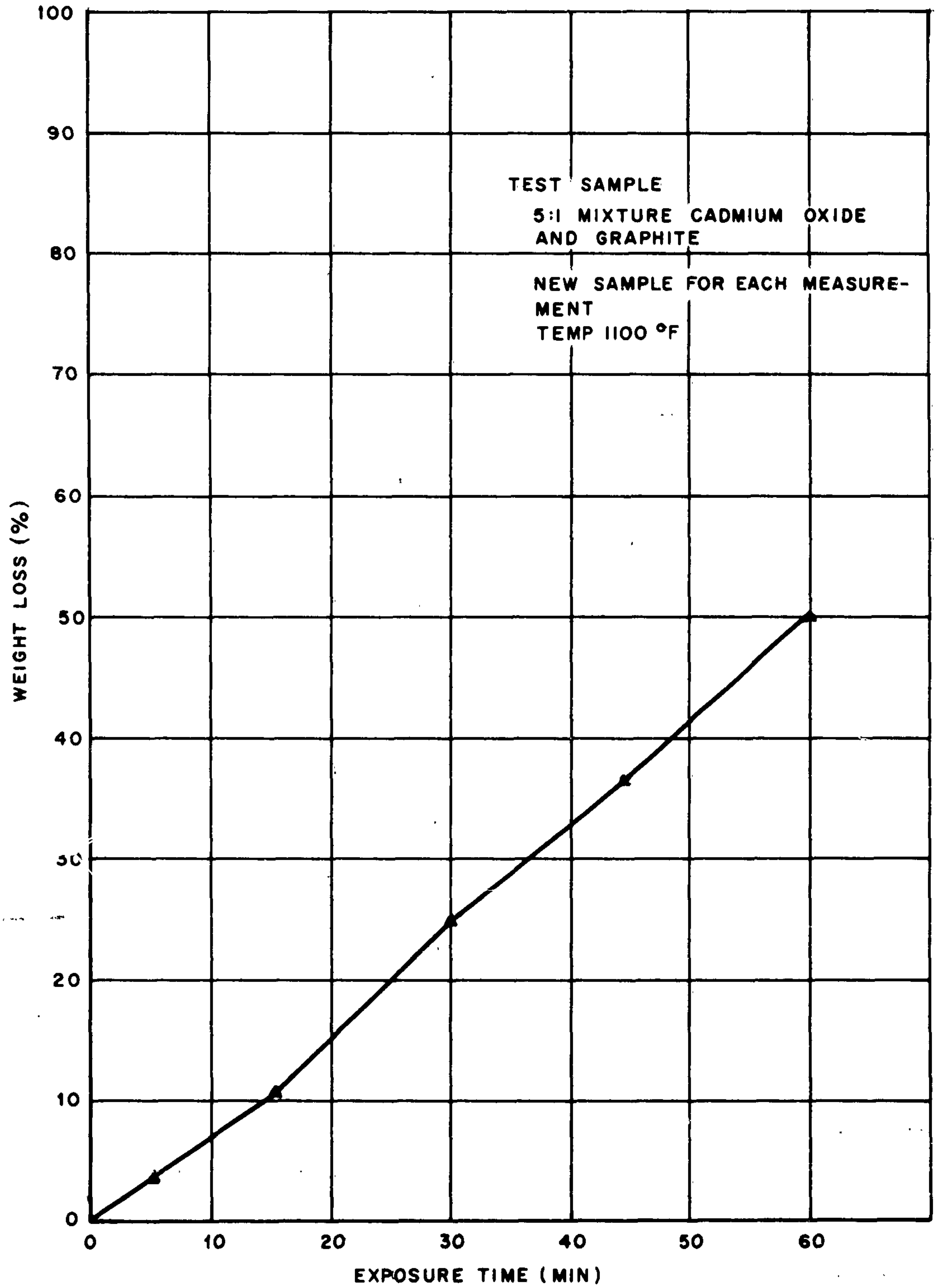


Figure 29. Weight Loss Versus Exposure Time

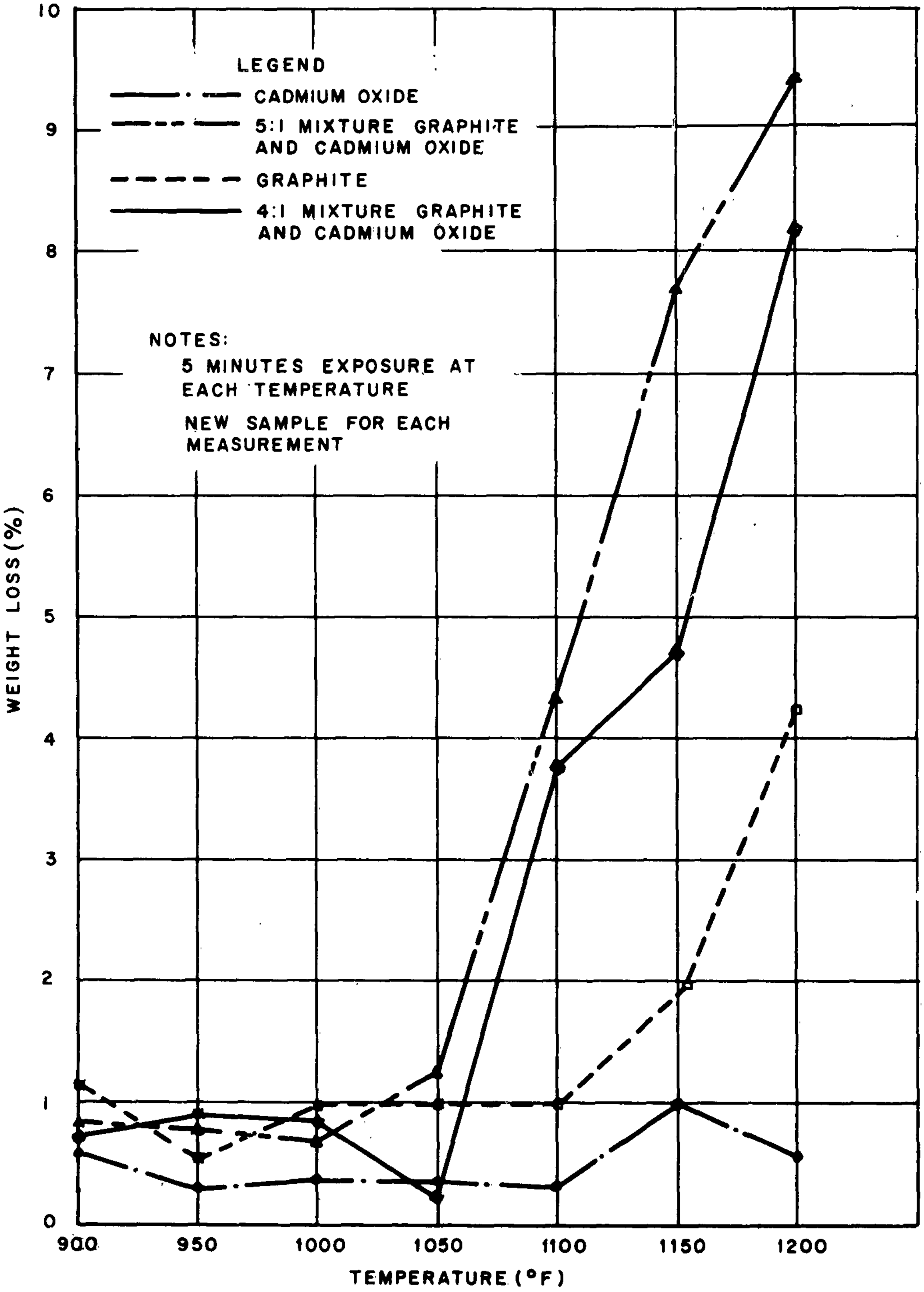


Figure 30. Weight Loss Versus Temperature

The following conclusions were derived from the oven experiments.

- Maintaining the exposure time constant at 5 minutes, the sample mixture loses about 3 percent of its weight for every 50° F incremental increase of temperature at temperatures from 1050° F to 1200° F.
- At a constant temperature of 1100° F, the sample mixture loses about 12 percent of its weight for every 15 minutes of exposure (about 1 percent per minute).
- Graphite begins to lose weight at a temperature of about 1100° F.
- The 5-to-1 lubricant mixture used for gear testing loses an insignificant amount of weight at temperatures below 1000° F. It is believed that the lubricant can be utilized at higher temperatures (up to 1200° F). The weight loss that would occur if the lubricant were exposed to higher temperatures would permit it to be used for limited periods of operation.

SECTION 7
CONCLUSIONS

This report describes the results of the latest portion of 4-1/2 years of research and development of lubricants for use with high-speed bearings and spur gears over the range from room temperature to 1200° F. During this period much knowledge and experience was gained to advance the state-of-the-art of powder lubrication techniques as applied to high-temperature lubrication. Major areas of achievement included the development of a successful powder lubricant, the methods and techniques involved in supplying the proper amount of lubricant having a particular concentration to the specific areas requiring lubricant, the designing of bearings and gears capable of being lubricated with powders, the investigation and screening of materials capable of successful operation under high-speed and high-temperature environments, and the design of test rigs and instrumentation for monitoring the performance of the bearings and gears.

Investigations and experiments over the past 1-1/2 years in the field of powder lubricants and their application to spur gears in the temperature range from ambient to 1200° F have evolved the following significant conclusions:

1. Spur gears operated successfully for periods of approximately 100 hours using lubricant powders and powder delivery techniques. The gears used in this evaluation were operated at a speed of 7400 rpm, loaded to 1000 ppi(tf) and cycled at temperatures from ambient to 900° F. The gears were made from M-50 tool steel and consisted of a 16-tooth and 15-tooth unit of 5 diametral pitch. The lubricant used was a mixture of 5 parts of micronized Acheson No. 38 graphite plus 1 part of cadmium oxide.

2. Tests were performed in which six sets of Rene' 41 gears were evaluated. Four tests were stopped within 4 hours because of excessive wear and abrasions of the gear teeth. The most successful test in this group continued for 19 hours and 10 minutes under conditions of 1000° F temperature, 440 ppi(tf) load, and 10, 350 rpm speed. The other tests were run at speeds of 15, 550 rpm. These results indicated that Rene' 41 gear material exhibits poor wear and hardness qualities when subjected to the required conditions. This conclusion was confirmed by Battelle Memorial Institute. (See Reference 1.)

3. Three tests were conducted using Haynes Stellite No. 151 gear material. The initial test ended in a failure after 2-1/2 hours but the test rig was then modified to enable the gear speed to be gradually increased to the operating speed of 15, 550 rpm. The following two tests lasted 26 and 28 hours until failure at test conditions of 1000° F and 685 ppi(tf) load.

4. Tests were run using Haynes Stellite Alloy No. 151 gear operating with a Rene' 41 gear. This test resulted in failure after 15 hours at test conditions of 15, 550 rpm, 950° F, and a load of 629 ppi(tf). The 151 gear had six teeth stripped off while the Rene' 41 gear had a portion of its teeth bent.

5. Haynes Stellite No. 6B gears were used in three tests. The most promising results were obtained from these investigations. Two tests exceeded 49 hours of operation. The results of these tests were predictable from the data of the Battelle Memorial Institute rolling-disk experiments. (See Reference 1.)

6. A set of Haynes Stellite Alloy No. 151 gears that had been shot-peened at the tooth roots were operated for 6 hours when the gear teeth fractured. It appears that the shot-peening, which was intended to improve the fatigue qualities of the gears, was actually detrimental. Final conclusions should not be based on this one test, however. It is recommended that further investigations should be conducted into the merits of shot-peening for these applications.

7. The lubricant mixture was subjected to elevated temperatures in an oven during an investigation into the physical changes that would result from heating the lubricant. It was found that the sample of the lubricant (5 parts micronized Acheson No. 38 graphite plus 1 part cadmium oxide) was reduced in weight by about 12 percent after being subjected to a temperature of 1100° F for 15 minutes. When samples of the lubricant were exposed to elevated temperatures for 5 minutes, the mixture exhibited a 3 percent weight loss for each increment of 50° F increase over a temperature of 1050° F. The tests indicate that it would not be wise to store the lubricant in a high-temperature environment. Reuse of the lubricant would probably not be practicable.

8. It has been demonstrated during this program that spur gear operation using powder lubrication is feasible. With the experience gained in this program together with that gained in the previous bearing lubrication program, it is believed that the state-of-the-art is advanced sufficiently to justify application of these principles in the operation of gas-turbine engine system using powder mixtures and powder lubrication techniques.

Although the program objective of running gears at 15, 000 rpm at 1000° F and higher for 100 hours was not attained, the results of this program are significant in the light of the present state-of-the-art in high temperature gear materials.

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APPENDIX I

THE DESIGN OF A SET OF SPUR GEARS

FOR OPERATION AT HIGH TEMPERATURE

WITH POWDER LUBRICATION

TABLE OF CONTENTS

ILLUSTRATIONS

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INTRODUCTION

SUMMARY

This report covers the analysis, design, material evaluation, and selection, for spur gears used in the High Temperature research program carried out under Contract AF33(657)-8625.

The program objective was the development of design and material criteria to insure an operating life of 100 hours minimum for spur gears running at pitch line velocities between 4,000 and 30,000 feet per minute and at temperatures to 1200° F. The three factors affecting gear operating life are, tooth form, material, and lubrication. This report concerns itself solely with the first two factors, the third being the subject of a separate, detailed report.

For the purpose of obtaining comparable values for all parameters associated with tooth form analysis, the gear pitch diameter was fixed at 3.250 inches, the speed at 15000 rpm (12,750 ft/min, pitch line velocity) and the tangential tooth load was 500 lb/in of tooth face. Values were computed for dynamic load, beam strength, wear limit load, PVT or scoring factor, Hertz stress, contact ratio, and maximum sliding velocity, for gear teeth of selected pressure angles and diametral pitches.

Although analysis of the results showed the 25° pressure angle tooth of 12 diametral pitch to have the highest beam strength and wear limit loads, coupled with the lowest PVT factor, Hertz stress, and sliding velocity, the 20° pressure angle stub tooth of 12/14 diametral pitch was selected for test. This selection was made on the basis of its favorable comparison with the 25° pressure angle tooth and its availability without recourse to special tooling. Tooth forms having a 14-1/2° pressure angle were found totally unacceptable due to the high contact stresses, PVT values, and sliding velocities.

Evaluation of materials for high speed, high temperature spur gearing is dependent upon the following criteria:

1- Tensile Strength
2- Fatigue Strength
3- Wear Resistance
4- High Temperature Hardness
5- Creep Strength
6- Scoring or Scuffing Resistance
7- Ductility
8- Impact Strength

In addition, gearing operating in hot air or corrosive environments requires varying degrees of oxidation and/or corrosion resistance.

Program results indicate that Stellite 6B, a wrought cobalt nickel alloy, has the greatest potential for achieving the program objective, with Haynes 151, a cast Cobalt base superalloy, and Rene′ 41, a forgeable high temperature nickel base alloy, showing not as much potential.

Gear sets were fabricated from each of the three materials, all gears being identical to insure repetitious contact between mating teeth, thus simulating the worst possible wear conditions.

Running tests of these gears, at 15000 rpm and 3.250 pitch dia., would result in 90 million tooth-to-tooth contacts for 100 hours of operation. In order to simulate the complete range of operating speeds, a test schedule was established, as shown in Table 1 to insure complete compliance with program objectives.

TABLE 1

GEAR TEST SCHEDULE

Running Time Hours	Speed R.P.M.	Pitchline Velocity Ft/Min	Horse Power (500 lbs. Load Per Inch of Tooth)	No. of Contacts
30	30,000	25,500	96.63	54×10^6
15	25,000	21,250	80,525	22.5×10^6
15	20,000	17,000	64.42	18×10^6
15	15,000	12,750	48.315	13.5×10^6 90×10^6 = 100 Hrs)
15	10,000	8,500	32.21	9×10^6
15	5,000	4,250	16.105	4.5×10^6
105 Total				121.5×10^6 Total

NOMENCLATURE

a	Addendum of Gear Tooth
B	Width of Strip of Tooth Under Compressive Load
β_a	Arc of Approach
β_γ	Arc of Recess
c	Deformation Factor
C	Center Distance
d	Pitch Diameter
d_t	Total Tooth Deflection, Combined Bending and Compressive
D. P.	Diametral Pitch
e	Effective Error
E	Modulus of Elasticity
f_1	Force Required to Accelerate Masses as Rigid Bodies = HmV^2
f_2	Limiting Acceleration Load, or Load Required to Deform Tooth to the Amount of the Effective Error
f_a	Force Acting at Acceleration
f	Coefficient of Friction
F	Tooth Face Width
h_t	Whole Depth of Tooth
H	Factor = $\tan \phi\,(1-\cos \phi)/150\,\phi^2 \quad (1/R\ ) + 1/R\ )$ Used in Calculating f_1
I_{mp}	Polar Moment of Inertia
K	Stress Factor
K_1	Factor $\dfrac{1 - \nu^2}{\pi E}$ (Used in Calculation of Strip B)
K_m	Change Factor for Backlash Calculation
m	Effective Mass
m_1	Profile Contact Ratio
η	Gear Ratio

M_1 Measurement Over Wires

n Speed (Revs per Minute)

η_c Gear Efficiency

N Number of Teeth

p Circular Pitch

P Compressive Stress - Hertz (Used in PVT Value)

PVT Scoring Factor = P x V_s ft/sec x T

Q Ratio Factor

r Radial Dimension

r_f Minimum Calculated Fillet Radius

r_t Edge Radius of Generating Rack, Hob, or Grinding Wheel

R Pitch Radius

R_{a1} Radius to bottom of active profile

R_b Base Circle Radius

R_o Outside Radius

ρ Radius of Curvature

s_1 Distance of the Point of Contact From the Pitch Point When Teeth are Drawn to Scale of 1 D. P.

S Separating Force

S_b Beam Stress

S_s Shear Stress

S_t Flexural Endurance

T Distance Along the Line of Action From the Pitch Point to the Point Where PVT Value is Being Considered

T_o Tip Circular Thickness of Tooth

T_p Tooth Circular Thickness at Pitch Radius

T_{BC} Tooth Circular Thickness at Base Circle

T_q Torque

V	Pitch Line Velocity
V_r	Rolling Velocity
V_s	Sliding Velocity
W	Weight, lbs
W_b	Beam Strength
W_d	Dynamic, or Impact Load
W_s	Bending Load
W_t	Tangential Load
W_w	Wear Limit Load
x_1	Diameter of Wire
x	Tooth Form Factor
y	Tooth Form Factor
z	Length of the Line of Action
Ƶ	Elastic Form Factor
Z	Depth to Point of Maximum Shear
ϕ	Tooth Pressure Angle
ν	Poisson's Ratio

ANALYSIS AND DESIGN

For comparative analysis, the mechanical properties of René 41 at 1000° F were used throughout in computing values for W_b and W_w.

Gears were assumed to be aircraft quality operating under the following conditions:

Maximum error in action = .0005 in

(d) Pitch Diameter = 3.25 in

(V) Pitch Line Velocity = 12,750 f.p.m.

(F) Face Width = .250 in

(W_t) Tangential Load = 125 lb

Formulae used for Comparative Analysis

Dynamic Load, W_d, lbs.

from Ref. 4, p. 37, for aircraft quality gears

$$W_d = \frac{.05V(Fc + W_t)}{.05V + \sqrt{Fc + W_t}} + W_t \tag{1}$$

Values of c from Ref. 4, Table No. 7, p. 37

Tooth Beam Strength, W_b, lbs.

from Ref. 4, p. 37

$$W_b = S_{tP}F_y \tag{2}$$

S_t = 60000 p.s.i. (for René 41 at 1000°F)

y = Tooth form factors calc. for worst load condition (Ref. 3, pp. 41-44)

Wear Limit Load, W_w, lbs.

from Ref. 4, p. 39

$$W_w = dFKQ \tag{3}$$

where $$Q = \frac{2\ \text{Ngear}}{\text{Ngear} + \text{Npinion}}$$

and, K = Stress factor for steel on steel-based on Brinell surface hardness (gear & pinion) and pressure angle (from Ref. 4, Table No. 11, p. 39).

Scoring Factor, PVT
from Ref. 3, pp. 53-55

The factors in PVT are as follows:

P - Hertz contact pressure - calculated for both pinion tip and root (in most general case)

V - Sliding velocity in feet per second at point where P is calculated.

T - Distance along the line of action from the pitch point to the point where P is calculated.

Therefore, the calculation of PVT factor involves the solution of a series of equations.

First, the radius of curvature at the tooth tip,

$$\rho = \sqrt{R_o^2 - (R \cos \phi)^2} \qquad (4)$$

From this, the length of the line of action, z, is next calculated, i.e.

$$z = \rho_P + \rho_G - C \sin \phi \qquad (5)$$

ρ_P = Tip Radius, pinion

ρ_G = Tip Radius, gear

Next, the Hertz stress for the pinion tip and root are computed;

$$P_P = 5740 \sqrt{\frac{T_q}{Fz\, N_P} \quad \frac{C \sin \phi}{\rho_P (C \sin \phi - \rho_P)}} \qquad (6)$$

$$P_G = 5740 \sqrt{\frac{T_q}{Fz\, N_G} \quad \frac{C \sin \phi}{\rho_G (C \sin \phi - \rho_G)}} \qquad (7)$$

P_P = Hertz stress, pinion tip, p.s.i.

P_G = Hertz stress, pinion root, p.s.i.

N_P = No. of teeth, pinion

N_G = No. of teeth, gear

Finally, the PVT, or scoring factor is calculated as follows:

$$PVT_P = \frac{\pi n}{360} \left(1 + \frac{N_P}{N_G}\right) (\rho_P - R \sin \phi)^2 \; P_P, \text{ for pinion tip} \tag{8}$$

$$PVT_G = \frac{\pi n}{360} \left(1 + \frac{N_P}{N_G}\right) (\rho_G - R \sin \phi)^2 \; P_G, \text{ for pinion root} \tag{9}$$

Since, for this program, both gear and pinion were identical, Hertz stresses and PVT factors were also identical at tip and root.

The recommended safe limit for the PVT factor is 1,500,000.

Profile Contact Ratio (from Ref. 3, p. 55)

This is the average number of teeth in contact in the transverse plane and is calculated from the following equation;

$$m_1 = \frac{zN}{2 \cos \phi \pi R} \tag{10}$$

Sliding Velocity (from Ref. 1, p. 69)

$$V_s = V \frac{1}{R_1} + \frac{1}{R_2} \left(\sqrt{R_o^2 - R_b^2} - R_1 \sin \phi \right) \tag{11}$$

$$V_s = \frac{2V}{R} \left(\sqrt{R_o^2 - R_b^2} - R \sin \phi \right) \tag{12}$$

for this program,

$R_1 = R_2$

and

$R_b = R \cos \phi$

For R_o, this gives the highest values and is indicative of the relative wear life of the several tooth profiles under examination.

Table 2 summarizes the values calculated for the selected pressure angles and diametral pitches.

Examination of Table 2 shows the 25° P.A. tooth of 12 D.P. to have the highest beam strength and wear limit load, together with the lowest scoring factor, Hertz stress, and sliding velocity. The 20° P.A. Stub tooth, 12/14 D.P. shows the next highest use potential in view of the comparable values for beam strength, PVT factor, Hertz stress, and sliding velocity. The 14-1/2° P.A. profiles show the most undesirable characteristics.

On the basis of the favorable operating characteristics and the availability of standard tooling, the 20° P.A. Stub tooth, 12/14 D.P. was selected for test.

The selection of the tooth form and size having been made, detailed analysis and design calculations were made for the actual test gears and testing apparatus.

TABLE 2

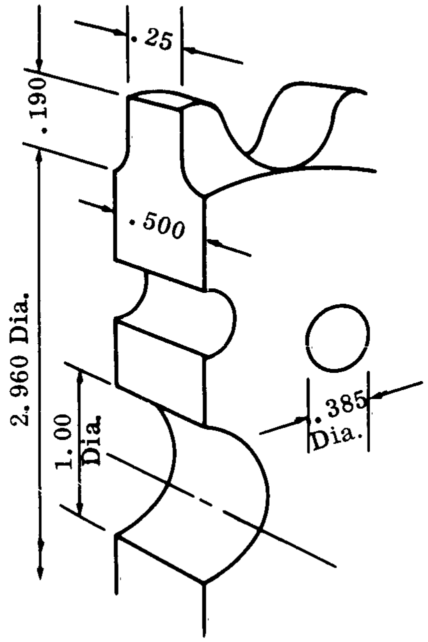
SUMMARY-CALCULATED DESIGN PARAMETERS
GEAR P.D. = 3.25 IN., FACE WIDTH = .25 IN.

Pressure Angle	Diam Pitch	N	$W_{d_{lb}}$	$W_{b_{lb}}$	$W_{w_{lb}}$	ρ in	z in	P_{psi}	PVT	m_1	V_s fpm
14-1/2°	8	26	441	976	203	.7664	.7191	179,190	6,064,680	1.89	5642
	12	39	441	709	203	.6658	.5179	104,621	1,835,909	2.04	4062
20°	8	26	448	1125	243	.8549	.5982	93,345	2,186,000	1.62	4693
	12	39	448	832	243	.7659	.4203	82,782	957,200	1.71	3298
	8/10 stub	26	455	1270	243	.8024	.4933	96,680	1,539,883	1.34	3870
	12/14 stub	39	455	861	243	.7390	.3665	86,933	764,181	1.49	2875
25°	8	26	469	1388	325	.9453	.5170	82,174	1,437,470	1.45	3980
	12	39	469	931	325	.8657	.3578	77,394	648,554	1.51	2807

Detailed Analysis - 12/14 Stub Tooth, 20° Pressure Angle.

Figures 1 through 19 and table 3 comprise the detailed analysis and design for the 12/14 stub tooth, 20° pressure angle test gears.

Polar Moment of Inertia, I_{mp}



$$39 \text{ teeth} \times .25 \times .190 \times .1309 \times .286 = .0694\#$$

$$\frac{\pi}{4}(2.960^2 - 1.00^2) \times .50 \times .286 = .9850\#$$

$$1.0544\#$$

$$-6 \times .5 \times \frac{\pi}{4} \times .385^2 \times .286 \qquad .100\ \#$$

$$.9544\#$$

Assume the simulated OD = 3.12

then $R_o = 1.56$

$R_i = 0.50$

$$I_{mp} = \frac{W(R_o^2 + R_i^2)}{772} = \frac{.9544(1.56^2 + .5^2)}{772}$$

$$= .003318 \text{ lb. in sec.}^2$$

Effective Mass (at pitch line), m $= \dfrac{I_{mp}}{(\text{Pitch Rad})^2} = \dfrac{.003318}{1.625^2}$

$$= .0012565 \ \frac{\text{lb. sec.}^2}{\text{in.}}$$

Acceleration Load on Tooth, f_a (Ref. 1, pp. 426-452)

$$f_a = \frac{f_1 f_2}{f_1 + f_2}$$

$$f_a = \frac{301.671 \times 321.113}{301.671 + 321.113}$$

$$= \underline{155.544 \text{ lb.}}$$

$$f_1 = HmV^2$$

for 20° P.A. Gears

$$H = .00120 (1/R_1 + 1/R_2)$$

Figure 1. Acceleration & Impact Load Calculations (Sheet 1 of 3)

$$= .00120 \times \frac{2}{1.625} = .0014769$$

$$f_1 = .0014769 \times .0012565 \times 12750^2$$

$$= \underline{301.671 \text{ lb.}}$$

$$f_2 = W_t \left[(e/dt) + 1\right] \qquad e = .0005 \text{ in.}$$

for 20° stub, $d_t = 8.7\left(\frac{W_t}{F}\right)\left[\frac{1}{E_1} + \frac{1}{E_2}\right]$ René 41 at 1000°F, $E = 27.3 \times 10^6$

$$= 8.7\left(\frac{125}{.25}\right)\left[\frac{2}{27.3 \times 10^6}\right]$$

$$= .00031869$$

$$f_2 = 125 \left[\frac{.0005}{.00031869} + 1\right] = 125 \times 2.5689$$

$$= \underline{321.113 \text{ lb.}}$$

Figure 1. Acceleration & Impact Load Calculations (Sheet 2 of 3)

Impact, or Dynamic Load, W_d

$$W_d = W_t + \sqrt{f_a\,(2f_2 - f_a)}$$

$$= 125 + \sqrt{155,544\ (2 \times 321.113 - 155.544)}$$

$$= 125 + 271 = \underline{396 \text{ lb.}}$$

When W_t = 250 lb. (Max. Load at 1000 #/in. of tooth face)

$$d_t = 8.7 \times \frac{250}{.25}\left[\frac{2}{27.3 \times 10^6}\right] = .00063736$$

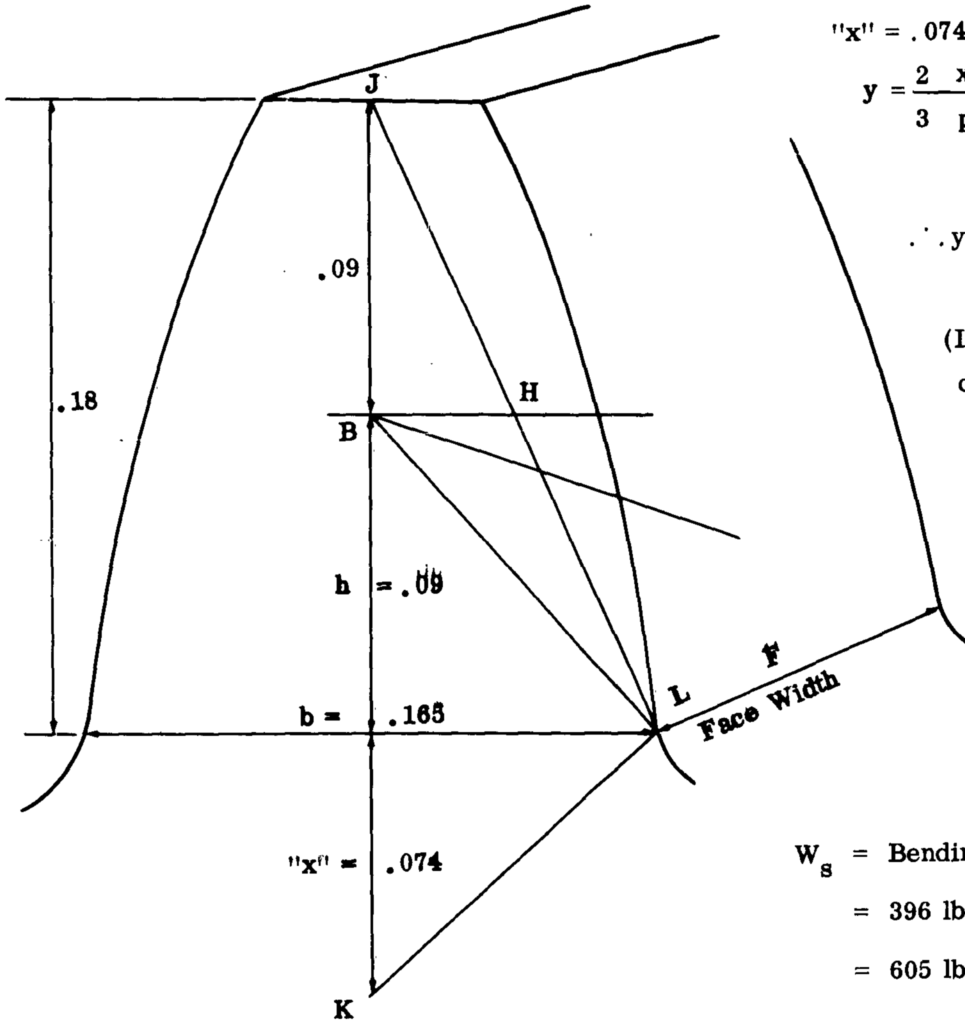
$$f_2 = 250\left[\frac{.0005}{.00063736} + 1\right] = 446.12 \text{ lb.}$$

$$f_a = \frac{302 \times 446}{302 + 446} = 180 \text{ lb.}$$

$$\therefore\ W_d = 250 + \sqrt{180\ (892 - 180)} = 250 + 358 = 605 \text{ lb.}$$

Note: In the case $f_2 < f_1$, tooth deformation will occur resulting in a proportionate decrease in acceleration.

Figure 1. Acceleration & Impact Load Calculations (Sheet 3 of 3)



"x" = .074 from Figure 17

$$y = \frac{2}{3}\frac{x}{p} \qquad P = .264$$

= circ. pitch at 1200° F

$$\therefore y = \frac{2}{3} \times \frac{.074}{.264} = .187$$

(Load assumed near center of tooth)

W_s = Bending Load

= 396 lbs (500 lbs/inch)

= 605 lbs (1000 lbs/inch)

Beam Stress (500 lbs/inch) $\quad S_B = \dfrac{W_s}{PFy} = \dfrac{396}{.264 \times .250 \times .187} = \underline{32,180 \text{ P.S.I.}}$

Beam Stress (1000 lbs/inch) $\quad S_{B_{max}} = \dfrac{605}{.264 \times .250 \times .187} = \underline{49,200 \text{ P.S.I.}}$

Both these values apply to a pitch line speed of 12,750 ft/min (15000 r.p.m.)

Figure 2. Beam Stress Calculations

Actual Value of d_t using Layout Values of "y"

Load Near Tip of Tooth $\quad x_t = .04 \therefore y_t = \dfrac{2 \times .04}{3 \times .2618} = .102$

Load Near Middle of Tooth $\quad x_m = .074 \therefore y_m = \dfrac{2 \times .074}{3 \times .2618} = .188$

$$d_t = (W_t/F)\left[\frac{1}{E_1 Z_1} + \frac{1}{E_2 Z_2}\right] \text{ (Ref. 1, p. 443)}, \quad Z = \frac{y}{.242 + 7.25\,y}$$

$\therefore$ If $Z_1 = Z_2$ and $E_1 = E_2$

$$d_t = \frac{1}{Z_1}(W_t/F)\left[\frac{2}{E}\right]$$

$$Z_t = \frac{.102}{.242 + 7.25\,(.102)} = .104$$

$$Z_m = \frac{.188}{.242 + 7.25\,(.188)} = .117$$

Deformation at Pitch Line Under Applied Load W

Assume Load Near Middle of Tooth then $Z_1 = .117 = Z_2$ (When both gears are identical)

$$\frac{1}{.117} = 8.547$$

$$= d_t = 8.547\left(\frac{W_t}{F}\right)\left[\frac{2}{E}\right]$$

$$d_t = 8.547\left(\frac{125}{.250}\right)\frac{2}{27.3 \times 10^6}$$

$= .00031325"$ = Total Bending Deflection (at Mid Tooth) $\Big\{$ Combined Bending and Compressive Deformation

Load to Deform Teeth by the Amount of the Error $= f_2$

$$f_2 = W_t\left[\left(\frac{e}{d_t}\right) + 1\right] = 125\left[\left(\frac{.0005}{.00031325}\right) + 1\right] = 325 \text{ lbs.} \quad \text{(Ref. 1, p. 433)}$$

$$\text{Load/inch} = \frac{325}{.250} = 1300 \text{ lbs.}$$

Figure 3. Tooth Bending & Surface Deflection Calculations

Assume Coeff. Friction = .05 at 12750 ft/min

m = Gear Ratio = 1

$$\text{Efficiency} = \eta = 1 - \left[\frac{1 + \left(\frac{1}{m}\right)}{\beta_a + \beta_r}\right] \frac{f}{2} (\beta_a^2 + \beta_r^2) \quad \text{(Ref. 1, p. 401)}$$

$$\beta_a = \text{Arc of Approach (Driver)} = \frac{\sqrt{R_{o2}^2 - R_{b2}^2} - R_2 \sin \phi}{R_{b1}} \quad \text{(Ref. 1, p. 401)}$$

R_o = Outside Rad = 1.69643

R_1 = Pitch Rad = 1.625 = R_2

R_{b1} = Base Circ. Rad = 1.527

= R_{b2}

$$\beta_a = \frac{\sqrt{1.69643^2 - 1.527^2} - 1.625 \times .34202}{1.527}$$

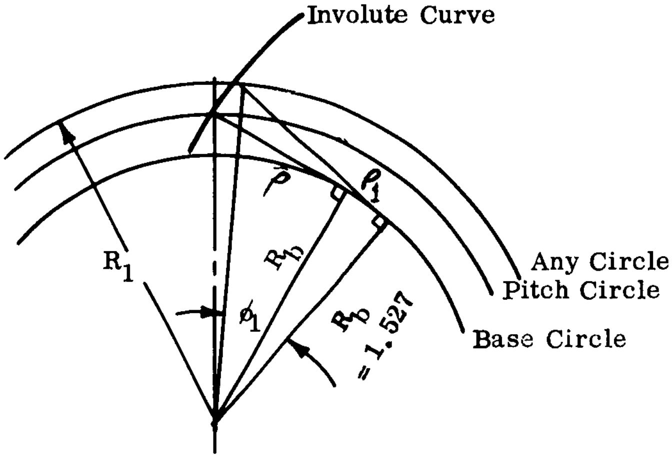
$$= \frac{.18323}{1.527} = .120$$

$$\beta_\gamma = \text{Arc of Recess (Driver)} = \frac{\sqrt{R_{o1}^2 - R_{b1}^2} - R_1 \sin \phi}{R_{b1}} = .120 \quad \text{(Ref. 1, P.401)}$$

$$\therefore \text{ Efficiency } \eta = 1 - \left[\frac{1 + \left(\frac{1}{1}\right)}{.12 + .12}\right] .05 \, (.12^2 + .12^2) = 1 - .012$$

$$= 98.8\%$$

Figure 4. Gear Efficiency



$$\cos\phi_1 = \frac{R_b}{R_1} \quad \sin\phi_1 = \frac{\rho_1}{R_1}$$

$$R_1 = \frac{R_b}{\cos\phi_1} = \frac{\rho_1}{\sin\phi_1}$$

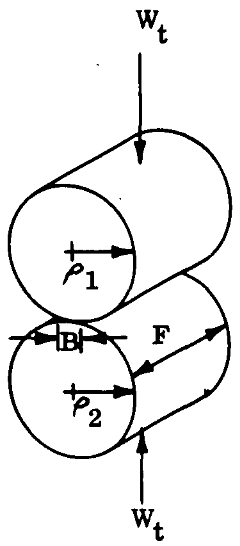
$$\rho_1 = R_b \tan\phi_1$$

R_1	$\cos\phi_1$	$\tan\phi_1$	ρ_1	T*
1.6964(R_0)	.90012	.48378	.73873	.183
1.660	.91988	.42636	.65105	.096
1.625(R)	.93969	.36397	.55578	0
1.590	.96038	.29021	.44315	.113
1.5718(R_{a1})	.97149	.24408	.37271	.183
1.527(R_b)	1	0	0	-

*At tip 2T = z = .366

Figure 5. Radius of Curvature at Various Positions on Tooth Flank

Cylindrical Approximation



At Tip of Tooth 1.6964 Rad. (Ref. 3, p. 48)

Width of Strip B

$$= \sqrt{\frac{16\ W_t\ (K_1 + K_2)\ \rho_1\ \rho_2}{F\ (\rho_1 + \rho_2)}}$$

$$B = \sqrt{\frac{16 \times 125\ (2.122 \times 10^{-8})\ .739 \times .373}{.250\ (.739 + .373)}}$$

$$= .006485$$

$E = 27.3 \times 10^6$ psi at 1000° F Rene′41.

where:

$\rho_1 = .739$

$\rho_2 = .373$

$W_t = 125$ lbs

$F = .250$

$\nu = .300$

$$K_1 = \frac{1 - \nu^2}{\pi E} = \frac{1 - .3^2}{\pi(27.3 \times 10^6)} = 1.061 \times 10^{-8} = K_2$$

$$\text{Max Comp Stress (Hertz)} = P = \frac{4W_t}{F \pi B} = \frac{4 \times 125}{.250\,\pi \times .006485} = 98,250 \text{ psi.}$$

Max Shear $S_s = .295\,P = .295 \times 98,250 = 29,000$ psi

Depth to Point of Max Shear $Z = .393\ B = .393 \times .006485 = .002549$

1.66 Rad.

$$B = \sqrt{\frac{16 \times 125\ (2.122 \times 10^{-8})\ .651 \times .443}{.250\ (.651 + .443)}} = .006767 \qquad \rho_1 = .651 \quad \rho_2 = .443$$

Figure 6. Hertz Stress at Various Positions on Tooth Flank
(Sheet 1 of 2)

$$P = \frac{4 \times 125}{.25\,\pi \times .006767} = 94{,}077 \text{ psi}$$

$$S_s = 27{,}300 \text{ psi}$$

$$Z = .00268$$

1.625 Rad.

$$B = \sqrt{\frac{16 \times 125\ (2.122 \times 10^{-8})\ .5558 \times .5558}{.250\ (.5558 + .5558)}} = .006868 \qquad \rho_1 = .5558 \qquad \rho_2 = .5558$$

$$P = \frac{4 \times 125}{.25\pi \times .006868} = 92{,}694 \text{ psi}$$

$$S_s = 27{,}300 \text{ psi}$$

$$Z = .0027$$

1.5718 Rad.

$$B = \sqrt{\frac{16 \times 125\ (2.122 \times 10^{-8})\ .373 \times .739}{.250\ (.373 + .739)}} = .006485 \qquad \rho_1 = .373 \qquad \rho_2 = .739$$

$$P = 98{,}250$$

$$S_s = 29000$$

$$Z = .002549$$

Figure 6. Hertz Stress at Various Positions on Tooth Flank
(Sheet 2 of 2)

(Ref. 3, pp 53-55)

$$z = \rho_P + \rho_G - C\cos\phi$$

where, ρ_P = radius of curvature at pinion tooth tip

ρ_G = radius of curvature at gear tooth tip

$$= .73873 + .73873 - 3.25\cos 20°$$

$$= 1.47746 - 1.11156 = .3659 = .366$$

$$P = 5740\sqrt{\frac{T_q C \sin\phi}{F \times z \times Np \times \rho(C\sin\phi - \rho)}}$$

$$= 5740\sqrt{\frac{203 \times 1.11156}{.25 \times .366 \times 39\rho(1.11156 - \rho)}}$$

$$= 45633\sqrt{\frac{1}{\rho(1.11156 - \rho}}$$

$$PVT = \frac{\pi n}{360}\left(1 + \frac{N_P}{N_G}\right)\left(\rho - R\sin\phi\right)^2 P$$

$$= \frac{\pi \times 15,000}{360}\left(1 + \frac{39}{39}\right)\left(\rho - .55578\right)^2 P$$

$$= 261.8P(\rho - .55578)^2$$

Radius	ρ	P	PVT
1.6964(R_o)	.73873	86,702	760,000
1.660	.65105	83,500	200,000
1.625(R)	.55578	82,100	0
1.590	.44315	83,500	277,400
1.5718(R_{a1})	.37271	86,700	760,000

Figure 7. Values of PVT Factor at Various Radii

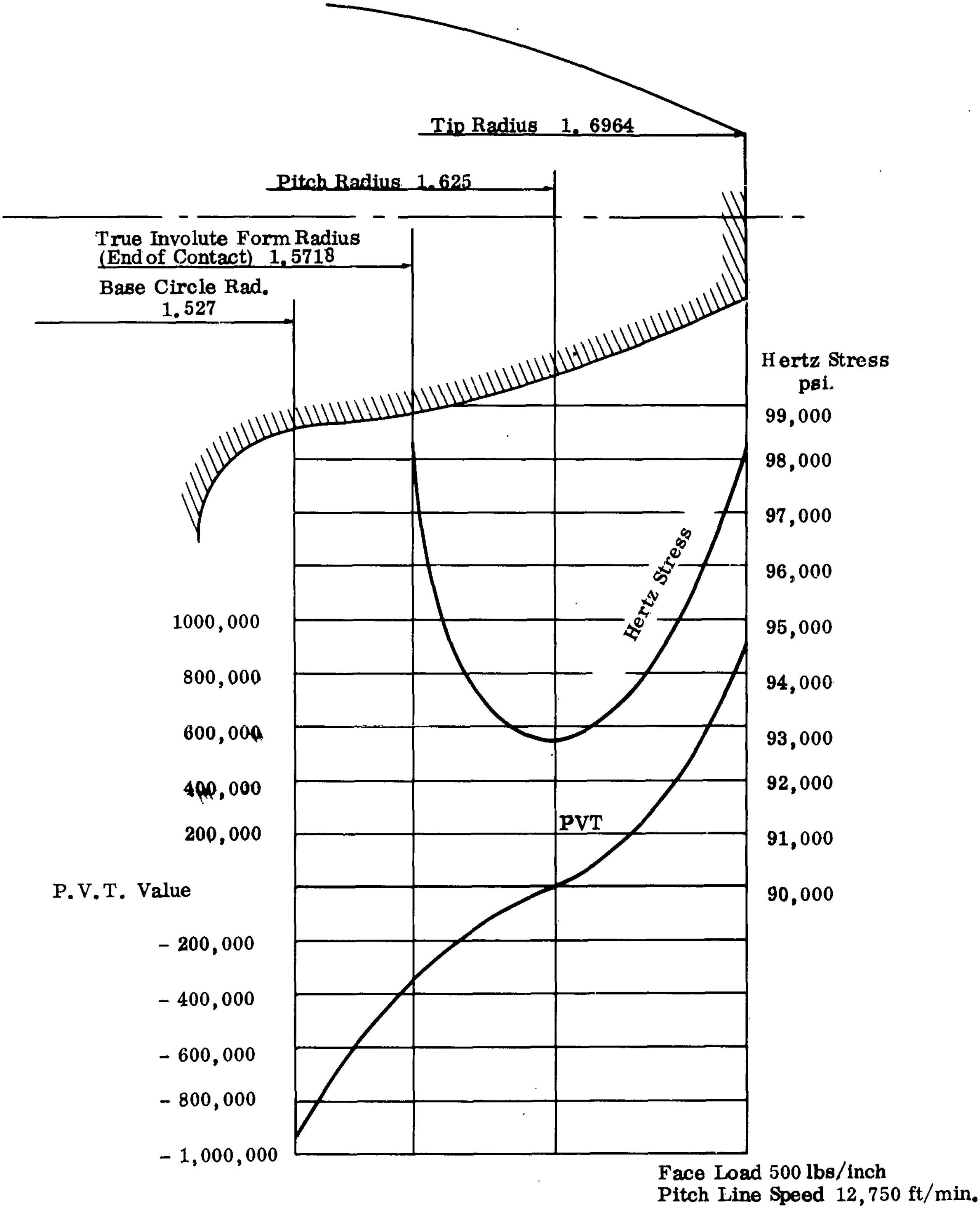


Figure 8. Graphical Presentation of Hertz Stresses and PVT Values

When R_1 = 1.66 (Ref. 1, p. 69)

$$V_s = V\left[\frac{1}{R} + \frac{1}{R}\right]\left(\sqrt{R_1^2 - R_{b1}^{\ 2}} - R \sin\phi\right)$$

$\sin\phi = .34202$

$$= 12750 \left[\frac{2}{1.625}\right] \left(\sqrt{1.66^2 - 1.527^2} - 1.625 \times .34202\right)$$

$R_{b1} = 1.527$

$R_o = 1.69643$

$$= 15692 \left(\sqrt{.42387} - .55578\right) = \textbf{1495 ft/min} = \textbf{24.92 ft/sec}$$

When R_1 = 1.527

$$V_s = 15692\ (0 - .55578) = -8721 \text{ ft/min.}$$

When R_1 = 1.575

$$V_s = 15692 \left(\sqrt{1.575^2 - 1.527^2} - .55578\right) = -2666 \text{ ft/min.}$$

When R_1 = 1.540

$$V_s = 15692 \left(\sqrt{1.54^2 - 1.527^2} - .55578\right) = -5588 \text{ ft/min.}$$

When R_1 = 1.535

$$V_s = 15692 \left(\sqrt{1.525^2 - 1.527^2} - .55578\right) = -6264 \text{ ft/min.}$$

When R_1 = 1.555

$$V_s = 15692 \left(\sqrt{1.555^2 - 1.527^2} - .5557825\right) = -4258 \text{ ft/min.}$$

$$R_{a1} = \text{Radius to bottom of active profile} = \sqrt{R_{b1}^{\ 2} + \left(C \sin\phi - \sqrt{R_o^{\ 2} - R_{b2}^{\ 2}}\right)^2}$$

$$= \sqrt{1.527^2 + \left(3.25 \times .34202 - \sqrt{1.69643^2 - 1.527^2}\right)^2} = \sqrt{2.470524} = 1.5718$$

When R_1 = 1.5718 (End of Contact)

$$V_s = 15692 \left(\sqrt{1.5718^2 - 1.527^2} - .5557825\right) = -2875 \textbf{ ft/min} = \textbf{47.91 ft/sec}$$

When R_1 = 1.6964

$$V_s = 15692 \left(\sqrt{1.6964^2 - 1.527^2} - .5557825\right) = 2860 \text{ ft/min.} = \textbf{47.67 ft/sec}$$

Figure 9. Sliding Velocities at Various Radii

For convenience the rolling velocities are **calculated by obtaining the value of "S_1"** from the sliding velocity. "S_1" is the distance of the point of contact from the pitch point when the teeth are drawn to a scale of 1 D.P. (Ref. 5, p. 71)

$$\text{Sliding Velocity } V_s = 2V \times S_1 \left(\frac{1}{N_1} + \frac{1}{N_2} \right)$$

$$\text{and } S_1 = \frac{V_s}{2V \left(\frac{1}{N_1} + \frac{1}{N_2} \right)}$$

V = Pitch Line Vel.
N_1 = Teeth in Driven Gear.
N_2 = Teeth in Driving Gear.

Having obtained S_1, the rolling velocity may be obtained from:

$$V_r = \left(\frac{N_1}{2\,D.P.} \sin \phi + \frac{S_1}{D.P.} \right) \frac{V \times 2\,D.P.}{N_1} \qquad \text{(Ref. 5, p. 71)}$$

<u>At tip - 1.6964 Rad.</u>

$$S_1 = \frac{2875}{2 \times 12750 \left(\frac{1}{39} + \frac{1}{39} \right)} = \frac{2875}{1308} = 2.2$$

$$V_r = \left(\frac{39}{2 \times 12} \times .34202 + \frac{2.2}{12} \right) \frac{12750 \times 2 \times 12}{39}$$

$$= (.556 + \frac{S}{P})\ 7850$$

$$= 5810 \text{ ft/min. (Layout scales 5850 ft/min)}$$

V_s = 2875 ft/min
D.P. = 12
N_1 = N_2 = 39
$\sin \phi$ = .34202
V = 12750 ft/min at 15000 rpm

<u>At 1.660 Rad.</u>, V_s = **1495 ft/min**

$$S_1 = \frac{1495}{1308} = 1.142 \quad \therefore \quad V_r = (.556 + \frac{1.142}{12})\ 7850 = 5110 \text{ ft/min.}$$

<u>At Pitch Rad - 1.625</u>, $V_s = 0$

$$S_1 = \frac{0}{1308} = 0 \qquad \therefore \quad V_r = (.556)\ 7850 = 4265 \text{ ft/min}$$

Figure 10. Rolling Velocities at Various Radii
(Sheet 1 of 2)

<u>At 1.575 Rad.</u>, V_s = **-2666 ft/min**

$$S_1 = \frac{-2666}{1308} = -2.04 \therefore V_r = (.556 - \frac{2.04}{12})\ 7850 = 3030 \text{ ft/min.}$$

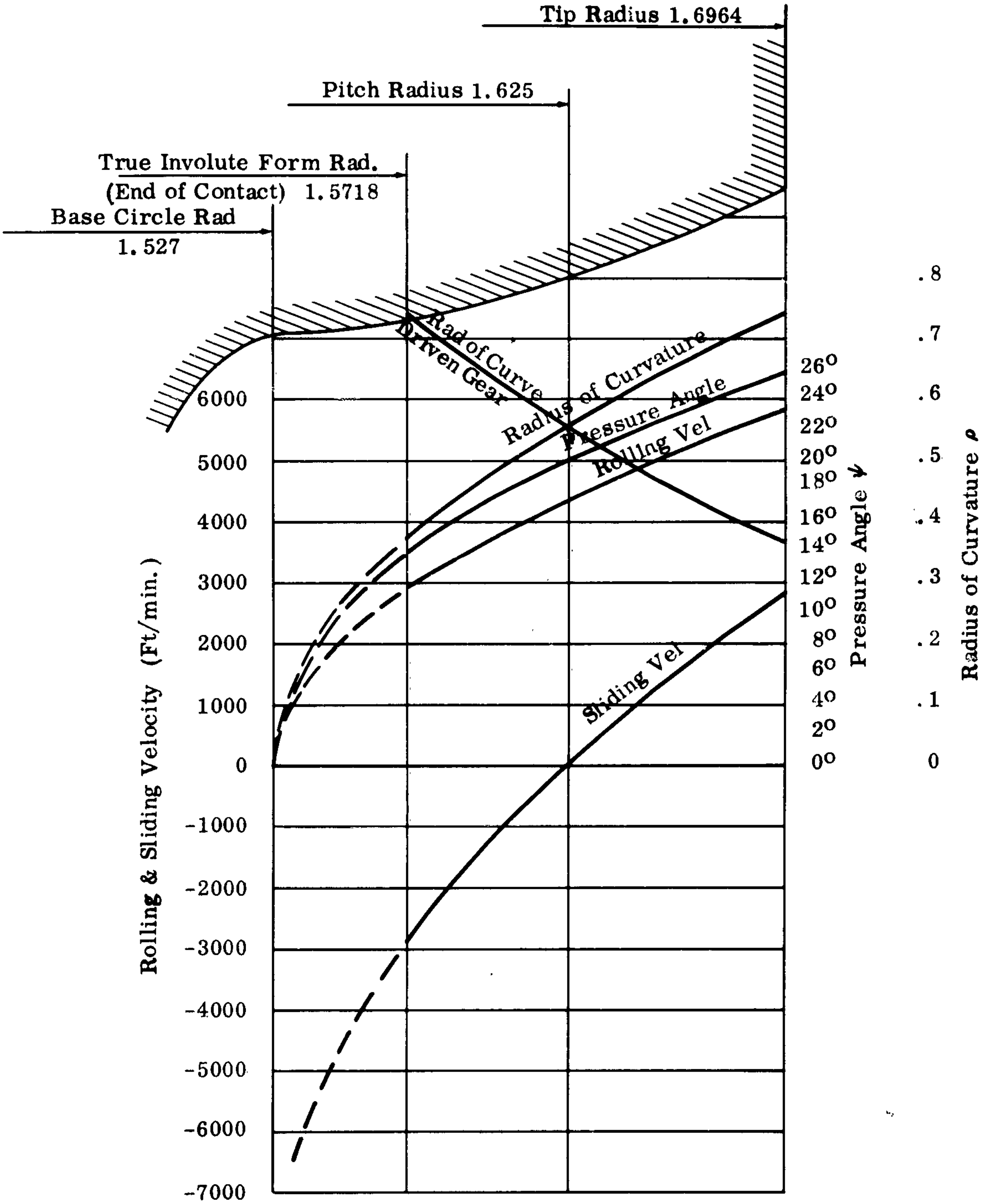
<u>At 1.527 Rad.</u>, V_s = **-8721 ft/min**

$$S_1 = \frac{-8721}{1308} = -6.67 \therefore V_r = (.556 - \frac{6.67}{12})\ 7850 = 0$$

<u>At 1.555 Rad.</u>, V_s = **-4285 ft/min**

$$S_1 = \frac{-4258}{1308} = -3.25 \therefore V_r = (.556 - \frac{3.25}{12})\ 7850 = 2240 \text{ ft/min.}$$

Figure 10. Rolling Velocities at Various Radii
(Sheet 2 of 2)



Face Load 500 lbs/inch
Pitch Line Speed
12750 ft/min

Figure 11. Graphical Presentation of Radii of Curvature, Pressure Angles, Rolling & Sliding Velocities

(Ref. 1, pp 79-81)

$$T_1 = 2\,R_1 \left[\frac{T_P}{2R} + \text{inv}\,\phi - \text{inv}\,\phi_1\right]$$

$$= 2\,R_1 \left[\frac{.1309}{2 \times 1.625} + .014904 - (\tan\phi_1 - \phi_1)\right]$$

$$= 2\,R_1 \left[.05518 - (\tan\phi_1 - \phi_1)\right]$$

where ϕ = pressure angle at pitch rad. R

ϕ_1 = pressure angle at radius R_1

$\text{inv}\,\phi = \tan\phi - \phi$ (rad)

and, $\cos\phi_1 = \dfrac{R_b}{R_1}$

For $\phi = 20°$, $\text{inv}\,\phi = .014904$

$R_b = 1.527$

R_1	$\cos\phi_1$	ϕ_1 deg	$\tan\phi_1$	ϕ_1 rad.	inv ϕ_1	T_1 70°F
1.527 (R_b)	1	0	0	0	0	.1685
1.5718	.97149	13°43'	.24408	.23940	.00468	.15875
1.577	.96829	14°28'	.25800	.25249	.00551	.15666
1.625 (R)	.93969	20°00'	.36397	.34907	.01490	.1309
1.650	.92545	22°16'	.40945	.38863	.02082	.11339
1.675	.91164	24°16'	.45082	.42353	.02729	.09343
1.696 (R_o)	.90012	25°49'	.48378	.45058	.03320	.07458

Figure 12. Tooth Thickness at Various Radii **(70° F)**

(From Ref 2, p. 5-24)

$$r_f = 0.7 \left[r_t + \frac{(h_t - a - r_t)^2}{\left(\frac{d}{\cos \psi^2}\right) + h_t - (a + r_t)} \right]$$

where ψ = helix angle (0° for spur gears)

From Ref. 2, p. 5-43, table 5-16 - Tooth form No. 6 has a transverse D.P. = 1 and shows an addendum = .71 and a value of r_t = .250 with a transverse ϕ = 20°;

$$\therefore \text{ when addendum } = .071,\ r_t = \frac{.250}{10} = .025$$

$$\text{and } r_t = \frac{.07143}{.71} \times .250 = .02515 \text{ (use .025)}$$

$$r_f = 0.7 \left[.025 + \frac{(.16786 - .07143 - .025)^2}{\left(\frac{3.250}{2 \cos^2 0°}\right) + .16786 - (.07143 + .025)} \right]$$

$$= 0.7\ (.025 + .003)$$

$$= .0196 \text{ Minimum fillet radius}$$

Root Dia $= 2\ R_b - 2 \times \text{clearance}$

$= 2\ (1.527 - .025)$

$= 3.004$ in.

clearance for ground teeth $= .35/DP$

$= .35/14$

$= .025$ in.

These values make no allowance for possible interference when the gears are operating at 1200° F. A 20 to 1 layout of the gear teeth shows that at 1200° F, with no allowance, .0125 interference will occur at the last point of contact. Radial clearance of .015 - 020 is considered satisfactory to allow for temperature variations. Projection from the point of contact indicates that reduction of R_{a1} from a value of 1.5718 to 1.5425 results in a radial clearance = .0175 at 1200° F. Since the True Involute Form Dia. = 2 x R_{a1}, the diameter specified on Figures 18, 19, & 20 = 3.085 in.

Figure 13. Minimum Fillet Radius & Root Dia. Calculation (at 70° F) (Sheet 1 of 2)

To reduce the stress concentrations at the tooth base, it was decided to provide a full rounded fillet. From the 20 to 1 layout, a full round fillet of .0464, tangent to the true involute form of adjacent tooth flanks at the 3.085 true involute Form Diameter, results in a root diameter of 2.990 in. This is specified on the applicable drawings as $2.990\ ^{+.000}_{-.010}$ Dia.

Figure 13. Minimum Fillet Radius & Root Dia. Calculation (at 70° F)
(Sheet 2 of 2)

Detailed Analysis - 12/14 Stub Tooth, 20° Pressure Angle

TABLE 3

TOOTH PROPORTIONS & VARIATION WITH TEMPERATURE

(For René 41 - coeff of thermal exp. = 7.8×10^{-6} in/in/°F)

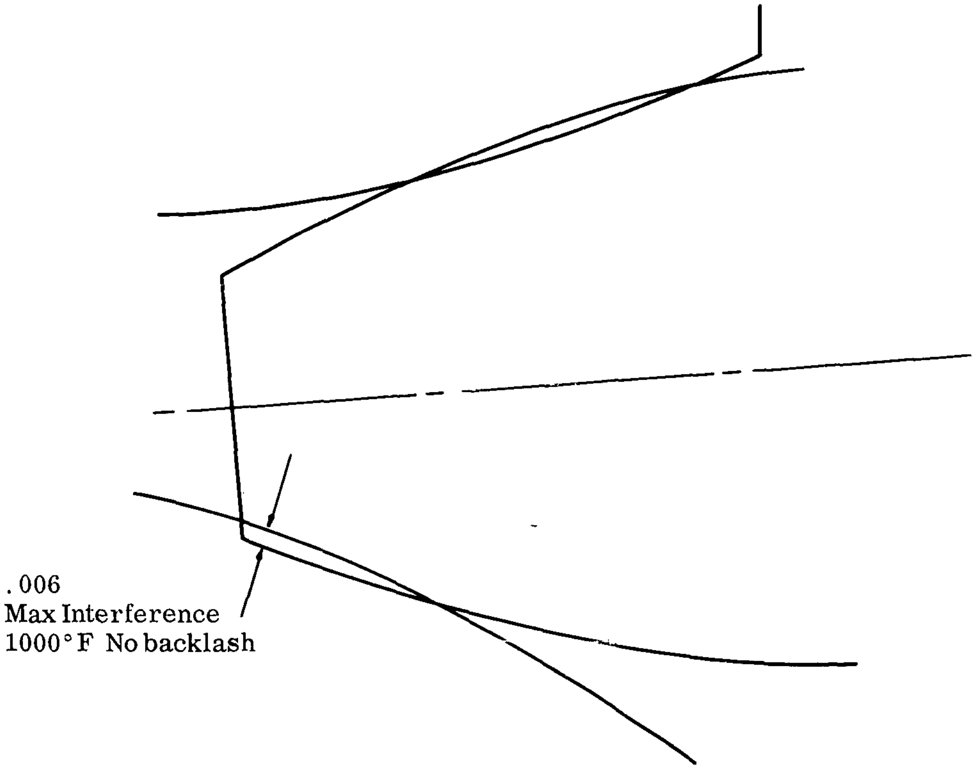
Temperature	70°F	1000°F	1200°F
Circular Pitch, $P = \frac{\pi}{D.P._1} = \frac{\pi}{12}$	.2618	.26376	.26416
Addendum, $a = \frac{1}{D.P._2} = \frac{1}{14}$	.07143	.07195	.07207
Dedendum (for ground teeth $= \frac{1.35}{D.P.2} = \frac{1.35}{14}$	.09643	.09713	.09728
Pitch Diam, d	3.250	3.2736	3.2786
O.D. = d + 2a	3.39286	3.41747	3.42277
Base Circle Dia. = d cos Ø	3.054	3.076	3.081
Radius to Bottom of Active Profile = R_{a1}	1.5718	1.5832	1.5857
Tooth Circular Thickness at R_o	.07458	.07512	.07524 *
Tooth Circular Thickness at R	.1309	.13186	.13205 *
Tooth Circular Thickness at R_b	.1685	.16972	.16996 *

* Basic Nominal Design Values, no allowance for backlash or tooth thinning.

Assume Housing Temp = 650° F

Expansion of 410 Stainless = $650 \times 3.25 \times 5.5 \times 10^{-6}$ = .01162

			.01162
			3.250
		New Centers	3.26162
Gear Pitch Dia. @ 1000° F	3.273575	Gear Pitch Dia. 200° F	3.27864
	3.261620		3.26162
Interference on the Pitch Dias.	.011955	Interference on Pitch Dia.	.01702



Recommended Min. Backlash for Gears of 12 D. P. = 003 to 005 (Ref 3, P. 83)

Assume .003 to .005 for **the Hot Gears Tooth** Thinning = $\frac{\text{Backlash}}{2}$ =		.0015	.0025
Allowance for the interference shown above	=	.0060	.006
Allowance for possible hard coatings	=	.0040	.004
Total Thinning		.0115	.0125
		.1309	.1309
True Circular Thickness at Pitch Radius		.0115	.0125
(Room Temp)		.1194	.1184 @ 70° F
		.1205	.1195 @ 1200° F

Backlash @ 70° F
Min = 2 x .0115 = .023
Max = 2 x .0125 = .025

Figure 14. Backlash and True Circular Thickness

(Ref. 2, pp 7-9 to 7-13)

x_1 Radius of Wire $\frac{1.728}{2 \times DP} = \frac{1.728}{2 \times 12} = .072$

T Arc Tooth Thickness at Pitch Rad. = .1309

ϕ_1 20°

ϕ_2 Pressure Angle at Center of Rolls

$$\text{Inv } \phi_2 = \frac{.1309}{2 \times 1.625} + (.3639700 - .3490658) + \frac{.072}{1.625 \times 9396926} - \frac{\pi}{39}$$

$$= .0402769 + .0149042 + .0471513 - .0805537$$

$$= .0217787$$

$$\phi_2 = 22.587851° \qquad \cos \phi_2 = .9232917$$

For odd teeth $R_2 = \frac{R_1 \cos \phi_1}{\cos \phi_2} = \frac{1.625 \times .9396926}{.9232917} = 1.6538657$

$$M_1 = 2(R_2 \cos \left[\frac{90}{N}\right] + x_1)$$

$$= 2(1.6538657 \times .99919 + .072)$$

$$= 3.449052 \text{ (No Backlash)}$$

Check from (Ref 2 Table 24-3) External Gears 20° Pressure Angle.

$$M_1 = \frac{\text{M for 1 DP}}{\text{DP of Gear}} = \frac{41.3886}{12} = 3.44905$$

Change Factor (For Backlash Allowance) $K_m = 2.45$

Test Gears		Dimensions Over Wires
For Min Backlash Teeth Are Cut Thin By .0115	Change = 2.45 x .0115 = .028175	3.4209 Max
For Max Backlash Teeth Are Cut Thin By .0125	Change = 2.45 x .0125 = .030625	3.4184 Min

Figure 15. Measurement Over Wires, M_1

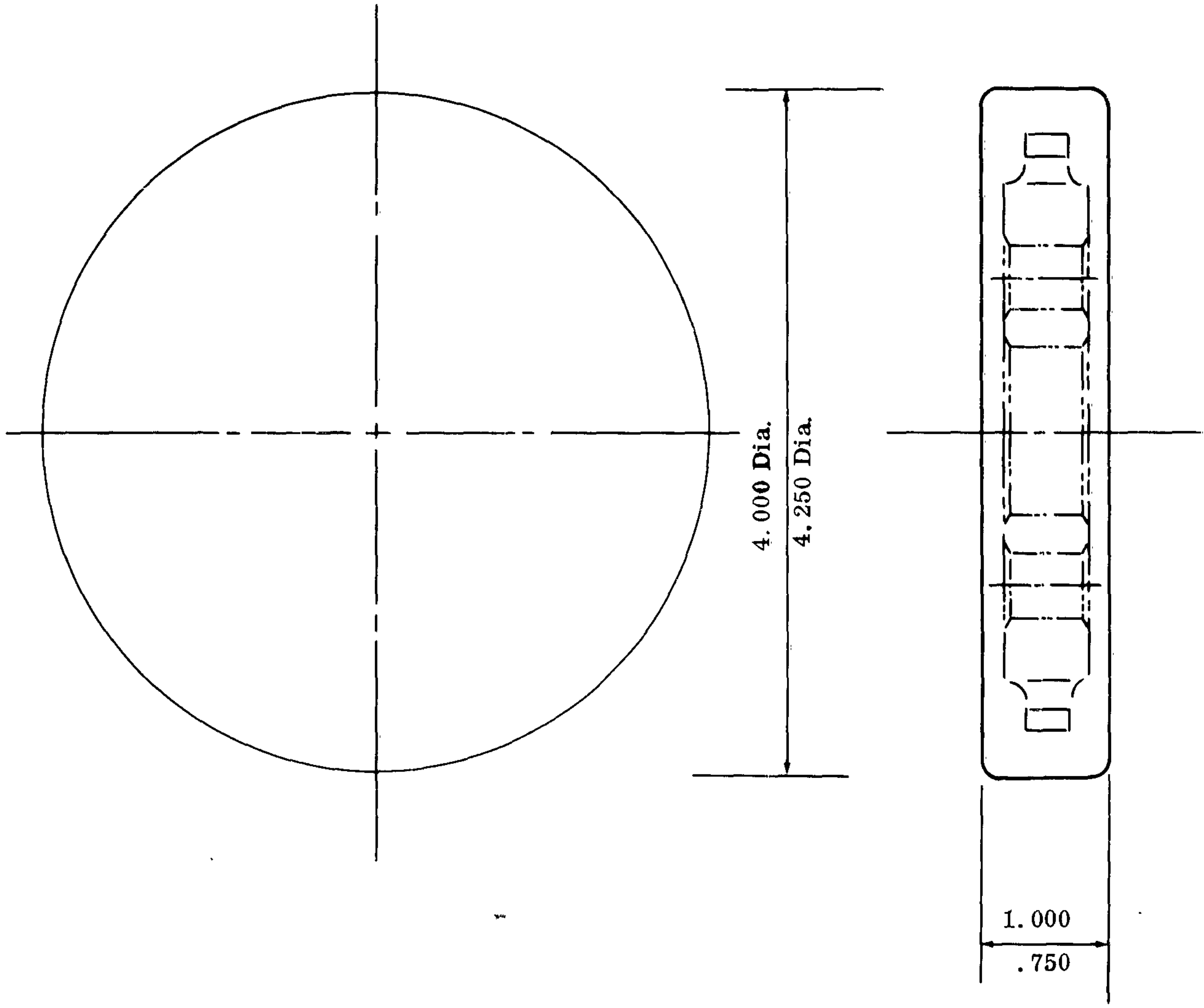


Figure 16. Forged Gear Blank

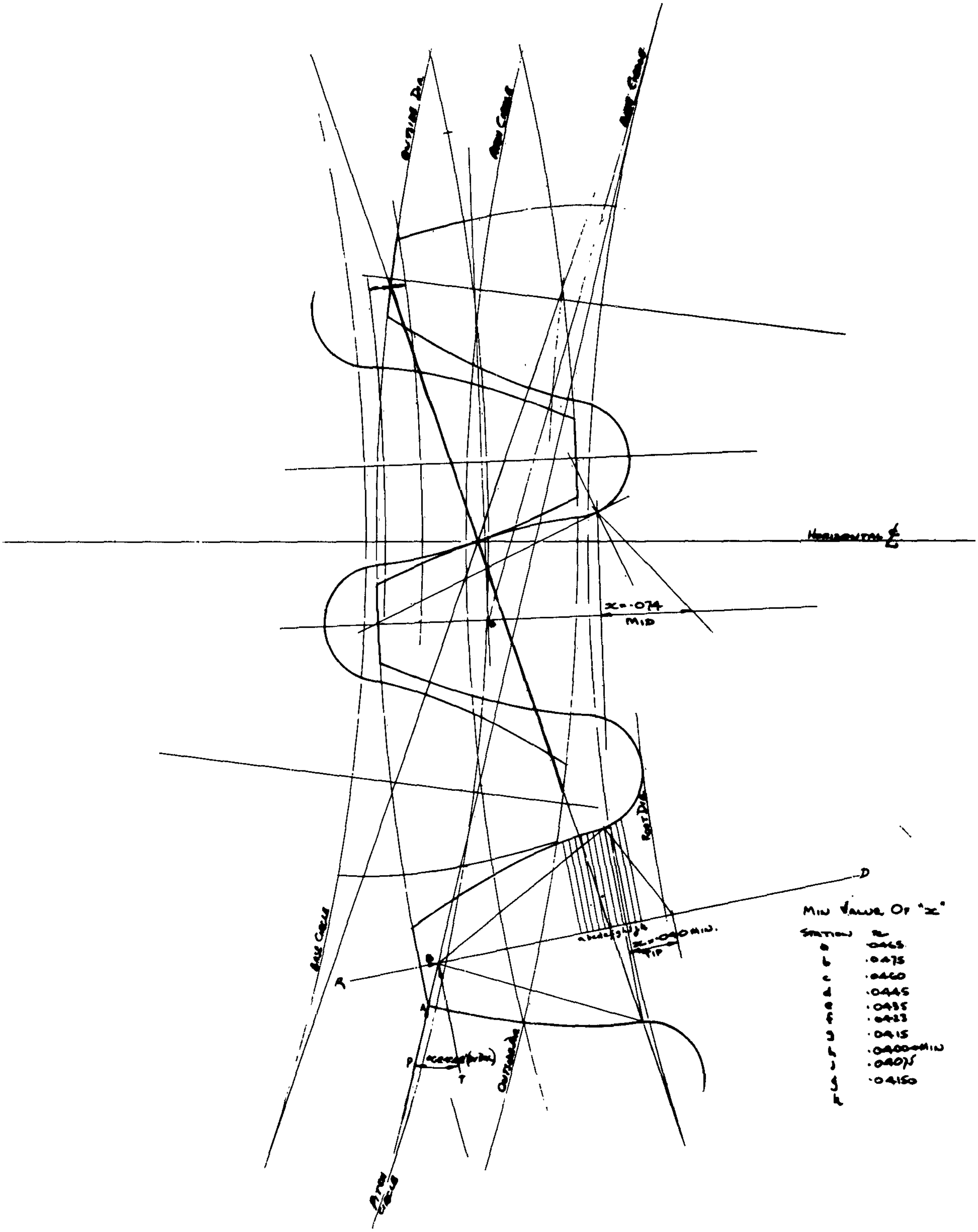


Figure 17. Gear Tooth Mesh at 1200° F

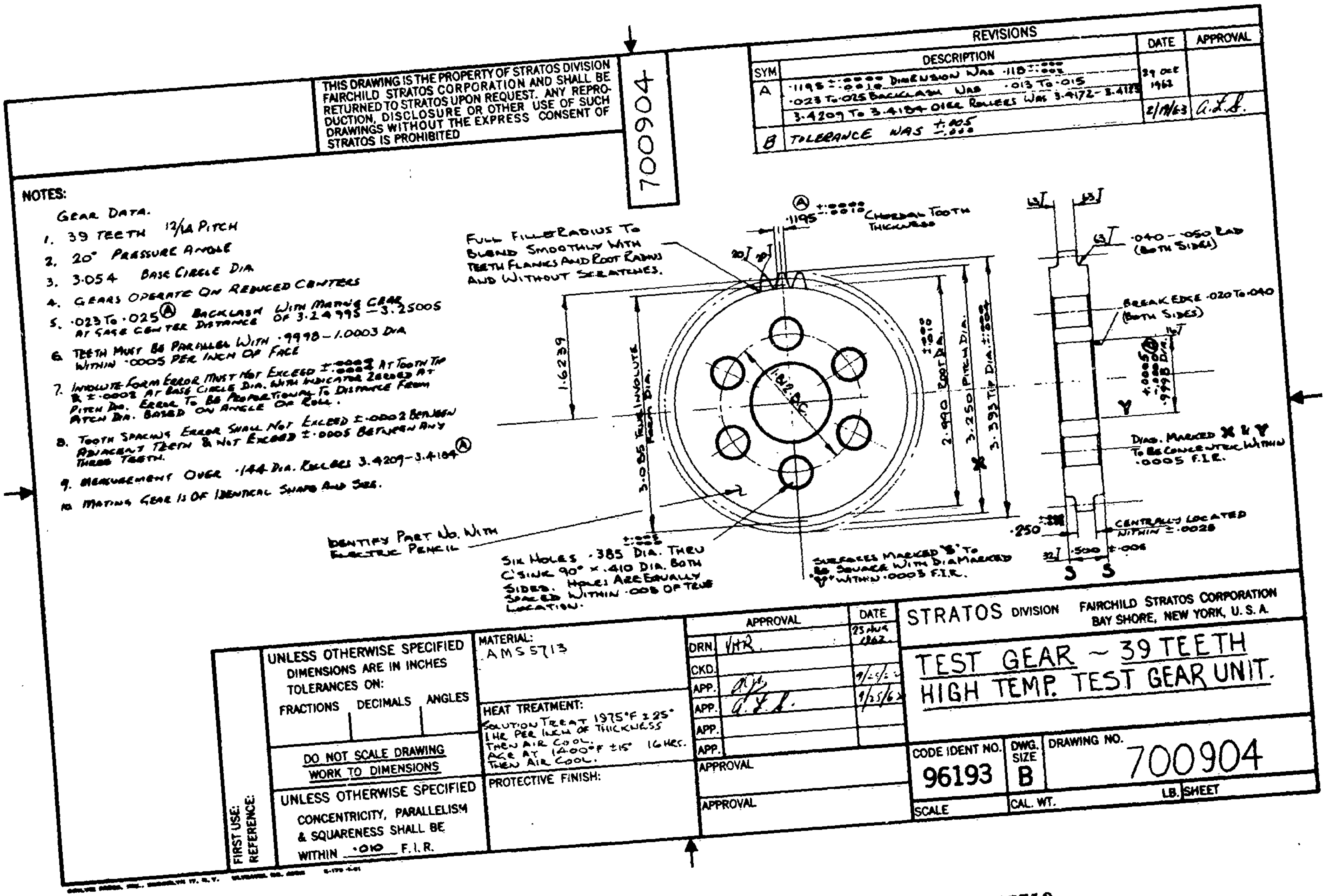


Figure 18. Test Gear - 39T - High Temp, Test Gear Unit - AMS 5713

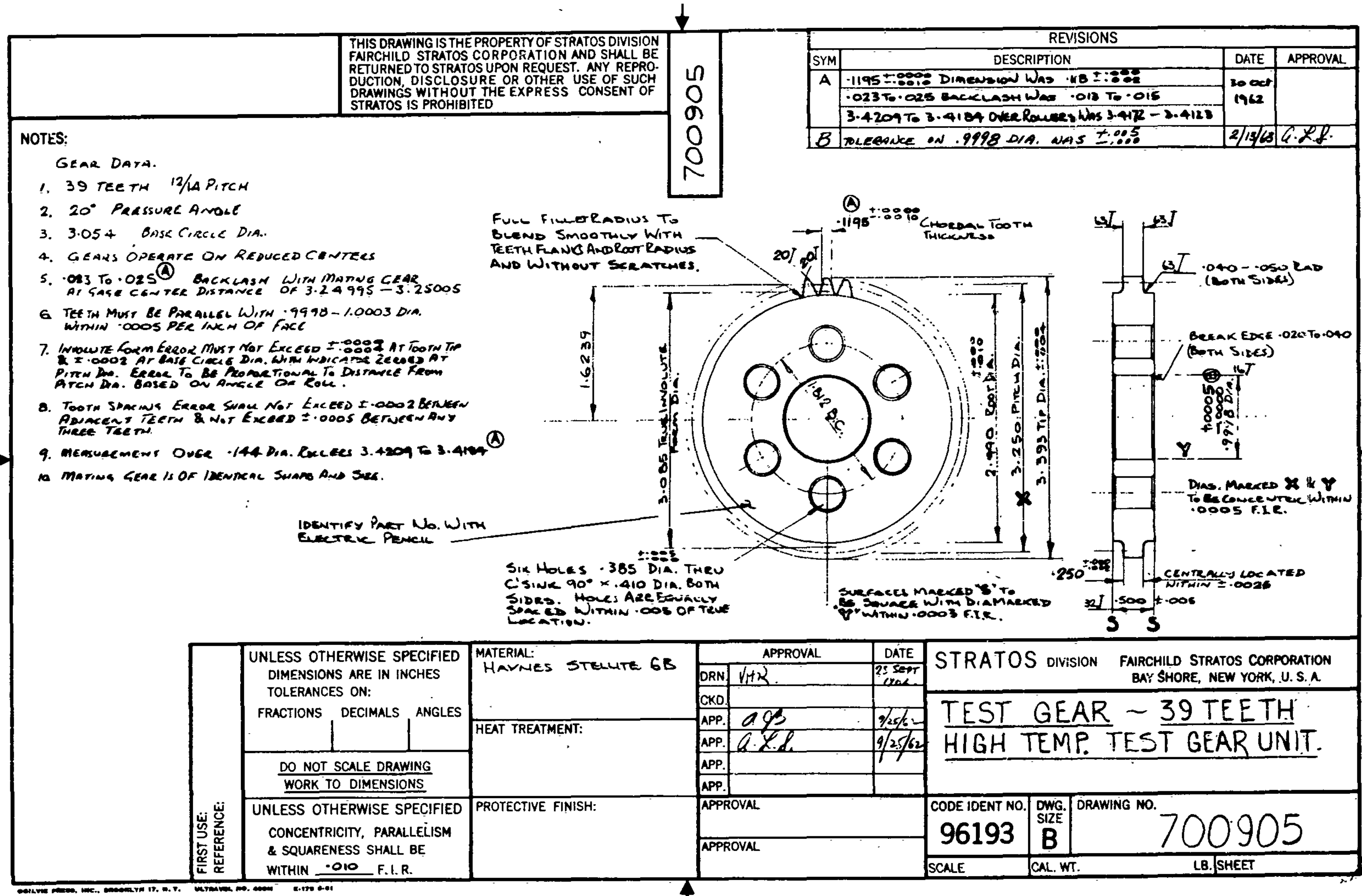


Figure 19. Test Gear - 39T - High Temp, Test Gear Unit - Haynes Stellite 6B

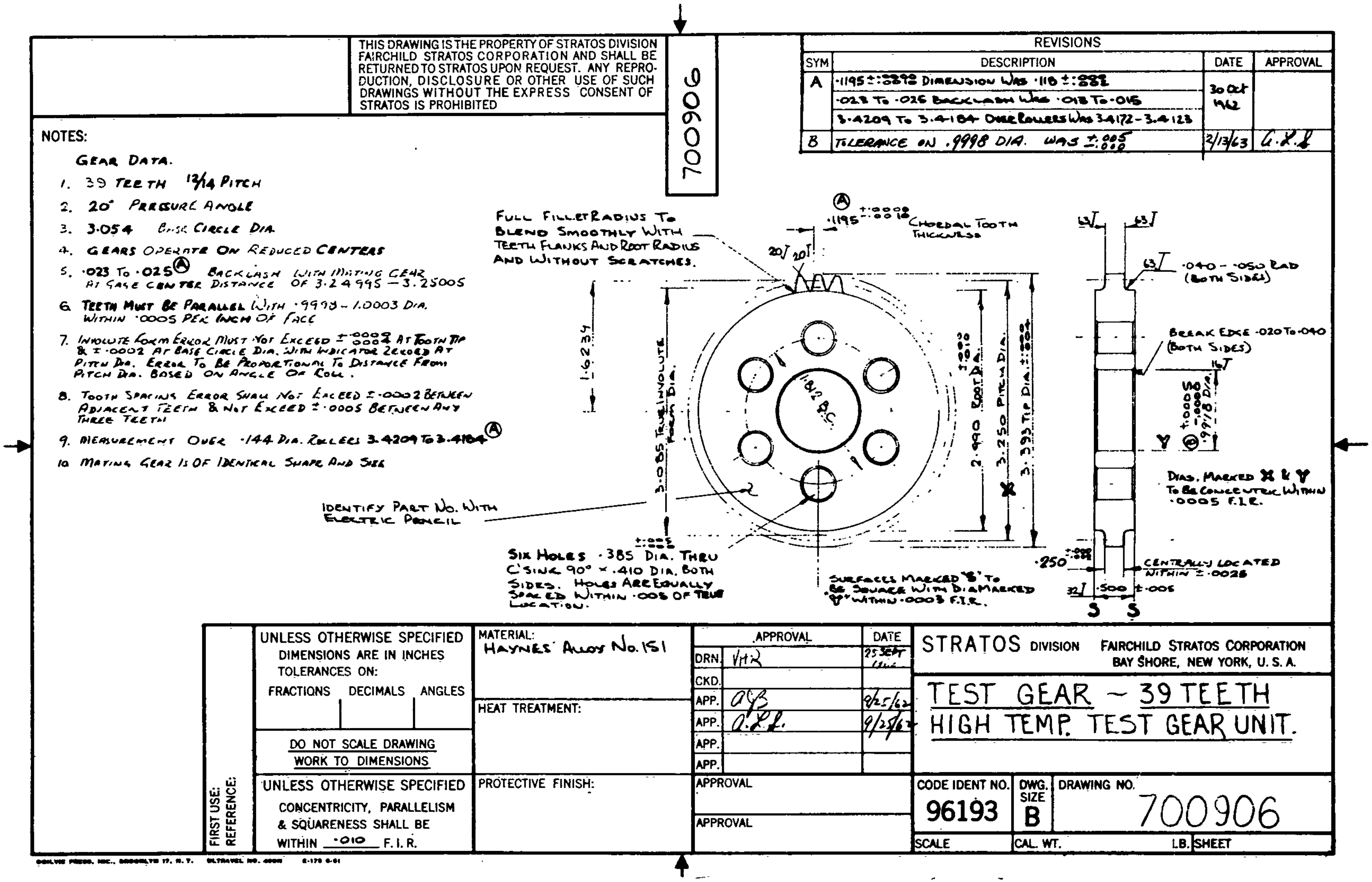


Figure 20. Test Gear - 39T - High Temp, Test Gear Unit - Haynes Alloy 151

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APPENDIX II

"DEVELOPMENT OF WEAR AND FRICTION INFORMATION FOR HIGH-TEMPERATURE GEAR MATERIALS AND LUBRICANTS"

By

Battelle Memorial Institute

TABLE OF CONTENTS

An experimental program has been carried out at Battelle to select appropriate gear materials for high-temperature spur gearing. The gears are requied to operate to 1000 F and 30, 000 rpm. The research has involved determination of wear and friction characteristics of selected potential gear materials under conditions simulating gear operation using a solid powder lubricant.

Selection of Gear Materials

High-temperature rolling and sliding contact applications require high hot hardness and creep strength. The reverse bending stresses on gear teeth necessitates fatigue resistance and high tensile strength. Sliding contact during meshing and disengagement of teeth requires wear and scuffing resistance. Since gears are also subjected to shock or impact loads, ductility and impact resistance must be considered. It is expected that the gear materials will be operated in air environments hence some degree of oxidation resistance is desired.

High-temperature gear materials were selected based on the following operating conditions:

Sliding speed	4560 ft/min
Rolling speed	6780 ft/min
Temperature range	RT to 1200 F
Time of operation	50 to 100 hours
Total number of stress cycles	90×10^6
Bending stress	39, 000 psi
Hertz stress	120, 000 psi

Materials potentially useful for this application fall into three classes; these are (a) the superalloy, (b) tool alloys, and (c) cermets. A summary of the properties of materials initially considered for evaluation is given in Table A1.

Three materials selected from this group include Rene '41, H.S. 151 and Haynes Stellite 6B. The Rene '41 material is a nickel base alloy with excellent high-temperature properties especially yield and fatigue. The cobalt base alloy H.S. 151 was chosen because of its high temperature properties and high hardness. The cobalt-chromium-tungsten tool alloy, Stellite 6B, was chosen for its high hot hardness and because it is a wrought cobalt tool alloy--providing greater toughness and shock resistance than a cast alloy.

In addition to these materials, Linde Company chromium carbide cermet, LC-1B40, coating for Rene '41 was evaluated in order to determine if the wear resistance of the high-temperature alloy could be improved by coating the surface with an abrasion resistant material.

M-50 tool steel was also investigated since available gear data on this material provided a convenient standard of performance evaluation.

The composition of these selected alloys are given in Table A2.

Apparatus

Combined rolling and sliding contact behavior were evaluated on two disk specimens, rolled together in a manner simulating gear action. The disk specimens are mounted on two parallel shafts which are three inches apart measured from center to center. One shaft consists of two sections joined by a flexible coupling. The section of this shaft on which the disk specimen is mounted is free to move in all directions in its self aligning pivot bearings. The shafts are geared to permit either rotation together, or one shaft can be held stationary while the other rotates to provide a sliding contact condition. For combined rolling and sliding, the disks are machined to different diameters and the shafts are geared to rotate at the same speed. The outside diameter of the disks are finished to a crown radius to help produce the desired contact stresses.

The disks are enclosed in a chamber which is heated by four 1250 watt radiant heat lamps capable of creating ambient temperatures to 2000 F. A dead weight load is applied to the disks through a steel cable wrapped around the movable shaft bearing housing. Friction torque is monitored by a strain gage assembly on the floating shaft support housing at the same point where the load is applied to the specimen. The stream of lubricant which is supplied by an air carrier is directed between the disk specimens at the point of contact.

Procedure

Disk specimens of 1.875 inch and 1.125 inch radius, respectively, were

TABLE A1. POTENTIAL HIGH-TEMPERATURE GEAR MATERIALS

Material	Temp, F	Wear and Galling Resistance	Friction, μ	Hot Hardness Brinell	Hot Hardness Rockwell	Young's Modulus, 10^6 psi	Impact, ft-lb	Elong, %	Lubrication	Fabrication, W=wrought C=cast	Tensile Strength, ksi	Yield Strength, ksi	Creep, hr/ksi	Thermal Exp., F x 10^{-6} RT to 1200 F	Reason for Choice
Super Alloys															
Rene 41	RT			290	C-30	31.6	2-5	15	None	W C	170	130		7.8	Excellent high-temperature properties and forgeable
	1400			-	-	24.8		10			130	100			
	1600	OK	0.25-0.47	-	-	23.2	6 8	20					20/25		
Hastelloy C	RT	OK		241	C-22	-28	21-23	48	Reactive gases and silver	W C	120	60		7.7	Good wear and friction, fair high-temperature properties
	1200			160	B-82			55			90	45			
	1500	OK	0.29-0.34	134	B-74	-20		55					10/25		
Haynes 25	RT	OK		225	C-20	35	193	29	PCH_2	W	145	67	20/30	8.2	Previous experience
	1500			120	B-72		130	16			56	35	@1500		
Haynes 151	RT	OK		315	C-33	-30	6	12	-	C	102	73	220/72	8.5	Excellent high-temperature properties
	1500			-	-		8	9			62	40	@1200		
Tool Alloy															
98M2	RT	Poor in air	0.1 gas	627	C-57	39.8	3	Nil	Reactive gases	C	95	95	-	7.1	Good wear properties; high hot hardness, but very brittle
	1500	Good in reactive gases	0.5 air	380	C-39										
Haynes Stellite 6	RT	Probably same as 98M2	0.1	350	C-36	30	9	3	-	C	115	96	1296/20	8.5	Most ductile of cobalt tool alloys
	1500			165	B-84		20	5			77		@1200		
Star J	RT	OK		600	C-56	37	3.5	Nil	PCH_2-MoS_2	C	75	75	220/40	7.3	Previous experience
	1500			395	C-41								@1200		
Stellite 3	RT	OK		580	C-53	33.7	6	Nil	PCH_2-MoS_2	C	85	85	5700/20	7.4	Previous experience
	1500			270	C-27								@1200		
Haynes Stellite 6B	RT	OK		380	C-39	30.4	72	11	-	W	146	92	169/40	8.7	Only wrought cobalt tool alloy available
	1500			-	-		126	16			74	45	@1200		
Cermets															
K161B	RT	Low against itself	0.3	~500 @1200	C-50 @1200	~50	Nil	Nil	C-CdO	Sintered	~100	100	-	5.3	Good wear properties
	1600														
K164B	RT	Probably not as good as other TiC cermets	-	~500 @1200	C-50 @1200	~50	1/2	0.99	C-CdO	Sintered	74	74	-	5.3	Good ductility and toughness for cermet
	1600						1/2	1.18	C-CdO		42	42			
K162B	RT	OK		604	C-56	55	Nil	Nil	C-CdO	Sintered	112	112	-	5.3	Previous experience
K162A1	RT	OK		538	C-52	57	Nil	Nil	C-CdO	Sintered	113	113	-	6.5	Previous experience
K175A	RT	OK		592	C-54	45	Nil	Nil	C-CdO	Sintered	124	124	-	5.3	Previous experience

TABLE A2. COMPOSITION OF ALLOYS

SELECTED FOR WEAR AND FRICTION EVALUATION

Alloy	Co	Cr	Mo	Fe	Ni	C	Al	Ti	W	Si	Mn	V
Rene '41	11	19	10	5	Bal	0.12	1.5	3.2	--	--	--	--
Haynes 151	Bal	20	--	2	--	0.47	--	0.15	12.8	--	--	--
Stellite 6B	Bal	30	1.5	3	3	1.1	--	--	4.5	2	2	--
M-50	--	4	4.25	Bal	--	0.8	--	--	--	0.15	0.25	1

machined from the materials selected for evaluation. The contact surfaces were coarse lapped to a crown radius of 10 inches and finished with number 10 grade diamond powder. The shafts were rotated at 7500 rpm and the disks were loaded to 110 pounds resulting in the following operating parameters:

Contact stress - 120,000 psi (maximum Hertz stress)
Sliding speed - 2900 feet per minute
Surface speeds (1.875 in. radius disk) - 7300 fpm
(1.125 in. radius disk) - 4400 fpm

The lubricant used in all evaluations was a mixture of cadmium oxide (CdO) and Acheson No. 38 grade graphite in a ratio of 1 to 5 by weight, respectively. The lubricant mixture was supplied in an air carrier (water compressed) at the rate of about 3/4 to 1 ounce per hour. The air pressure was maintained at 5 psig.

The temperature for all runs was 1000 F except for the tool steel disks which were operated at 900 F. The operating time for all specimens was 75 minutes except the Rene '41 disks which were run for 31 minutes.

Results

The results of the material evaluation are summarized in Table A3. Measurements of the change in geometry of the contacting surfaces caused by wear and plastic deformation are shown in Figures A1 through A5. These contour traces were obtained by traversing the disk crowns with an electrolimit gage over representative areas of the contacting surfaces.

TABLE A3. SUMMARY OF RESULTS OF THE ROLLING-DISK EVALUATIONS

Material	Operating Time minutes	Depth of Deformation, inch	Width of Deformed Zone, inch	Average Friction	Comments
Rene '41	31	0.0024	0.30	>0.1	Severe plastic deformation in small disk with scoring of both disks.
Haynes 151	75	0.0011	0.25	0.07	Deformation pronounced in small disk; some scoring and wear evident in both disks.
Stellite 6B	75	0.0006	0.20	0.08	Some deformation on both disks; only slight scuffing and wear.
Rene '41 coated with 1 mil LC-1B40 cermet	75	0.0048	0.50	0.09	Extreme deformation but surfaces comparatively smooth and free from scoring.
M-50	75	0.0058	0.50	0.30	Evidence of plastic deformation with only slight scuffing. Smeared metal quite evident.

Rene '41: The Rene '41 disks operated at moderate friction (0.09) during the first three minutes of operation. During the remaining 28 minutes, the friction increased and became erratic, varying between 0.35 and 0.11. The surface contour trace of the Rene '41 disks is shown in Figure A1. Extreme dishing of the small disk is evident. Although the disk surfaces were covered with a continuous film of lubricant, there was evidence of moderate scuffing.

In order to determine the extent of wear and plastic deformation, the disk specimens were sectioned normal to the rolling axis and metallographic analysis performed. The grains near the surface of the small specimen were severely distorted indicating considerable plastic deformation. Grain distortion in the large specimen could not be detected. The microhardness in the interior of the small specimen was 533 DPH while at the edge of the disk near the sliding surface it was 832 DPH. The average microhardness of the interior of the large disk was 520 DPH while for the edge it was slightly higher (534 DPH). The increase in hardness toward the surface of the small disk indicates considerable work hardening and is consistent with the observed heavy distortion of the surface grains. No conclusions could be drawn from the microstructure as to relative operating temperature levels for the disks.

Haynes Stellite 151: The cobalt alloy Haynes Stellite 151 exhibited a relatively low coefficient of friction, ranging between 0.06 and 0.07. Disk surfaces after running were covered with a continuous lubricant film. Surface damage was limited to scuffing and plastic flow. Figure A2 shows the results of the contour survey after disk operation. The larger amount of grooving or "dishing" of the disk crown was found on the smaller disk as observed in Rene '41. Comparing Figures A1 and A2, a greater amount of deformation is seen in the Rene '41 small disk than in the Haynes 151 small disk. This is in spite of the 75 minute operating time of the Haynes 151 compared to 31 minutes for Rene '41.

Stellite 6B: The cobalt tool alloy Stellite 6B showed more resistance to plastic flow than the Rene '41 and Haynes 151 alloys under similar operating conditions. The friction coefficient varied between 0.08 and 0.09. Examination of the surfaces after running revealed a continuous coating of lubricant with only slight scuffing and wear. The contour trace for this material is shown in Figure A3.

Flame Coating LC-1B40: Rene '41 disks, coated with the Linde Company chromium carbide cermet, LC-1B40, were evaluated to determine if the galling resistance of the Rene '41 could be improved.

The coefficient of friction for this material was 0.09 and unlike the uncoated Rene '41 disks there was no period of high and erratic friction. Examination of the contact surfaces indicated little or no scuffing, scoring, or metal transfer. The slight scoring and scuffing which was characteristic of the other materials was completely absent in the coated Rene '41 disks.

Considerable wear and/or deformation however did occur in the coated disks. Figure A4 shows the contour trace of the coated Rene '41 disks. The surface

of the small disk was highly concave and the deformed zone extended completely across the width of both specimens.

M-50 Tool Steel: M-50 tool steel disks were evaluated at 900 F as a basis of comparison for the candidate materials. The coefficient of friction for M-50 was measured as 0.3. Surface examination indicated that the disks were subjected to extreme plastic deformation. The surface contours are shown in Figure A5. There was a considerable amount of smeared metal on both large and small specimens. Both specimens were coated with lubricant and only slight scuffing of the surfaces occurred.

Conclusions

A comparison of the wear and friction behavior of the three materials, Rene '41, Haynes 151, and Stellite 6B, reveals that the Stellite 6B alloy has the greatest potential for high-temperature gears on the basis of friction, deformation, and resistance to surface scuffing as indicated in Table A3. Although none of the three materials showed outstanding scuffing resistance, extreme damage can be prevented with adequate lubrication.

A thorough investigation of the deformation and/or wear mechanism in the investigated materials was not performed, however the resistance to deformation and/or wear was in the order of their respective hardness.

The results of the coating experiments indicated that no great improvement in plastic deformation and/or wear of Rene'41 is achieved by flame plating a cermet coating. However, the contact surfaces of the coated disks appear to resist scoring better than the uncoated ones. The difference in the magnitude of contouring (plastic deformation and/or wear) between the coated and uncoated disks is proportional to the difference in operating time. Table A3 indicates that the depth of contouring doubled when the operating time increased from 31 to 75 minutes.

Comparing the performance behavior of the M-50 tool steel at 900 F with those of the high-temperature alloys at 1000 F, it can be concluded that the deformation resistance is similar to Rene '41 while the friction behavior is not quite as good. The scoring resistance of M-50 appears to be better than the high-temperature alloys and on a par with the cermet coating.

Greater amounts of deformation were found on the smaller disks of all materials investigated (see Figures A1-A5). This phenomenon is quite curious since the only obvious difference in operating conditions between the two is in the time of stress and contact duration. An elemental volume of material in the small disk is subjected to sliding and contact stresses for longer periods of time during a single rotation. At the high-temperatures used in this evaluation, creep which is a time dependent phenomenon may be a greater contributing factor to the deformation of the small specimen.

The results of the disk experiments were compared with the performance of M-50 and Rene '41 gears after 100 and 13 hours of operation, respectively. The Rene '41 gear which was operated at 2000 fpm sliding speed for most of its running time exhibited surface scuffing similar to the Rene '41 disks which were operated for 31 minutes at 2900 fpm. The Hertz contact stress for the gears was 81,700 psi while the disk contact stress was 120,000 psi.

The M-50 gears which were operated for 100 hours at 2900 fpm sliding velocity under 129,000 psi had very smooth contact surfaces with no evidence of scuffing. Gross plastic deformation in the gear teeth was not visible.

Although the M-50 disk specimens also did not exhibit scuffing, plastic deformation on the smaller disk was quite noticeable. The smearing on the disk surfaces indicate that the instantaneous surface temperature may have been considerably greater than 900 F, thus accounting for the plastic deformation.

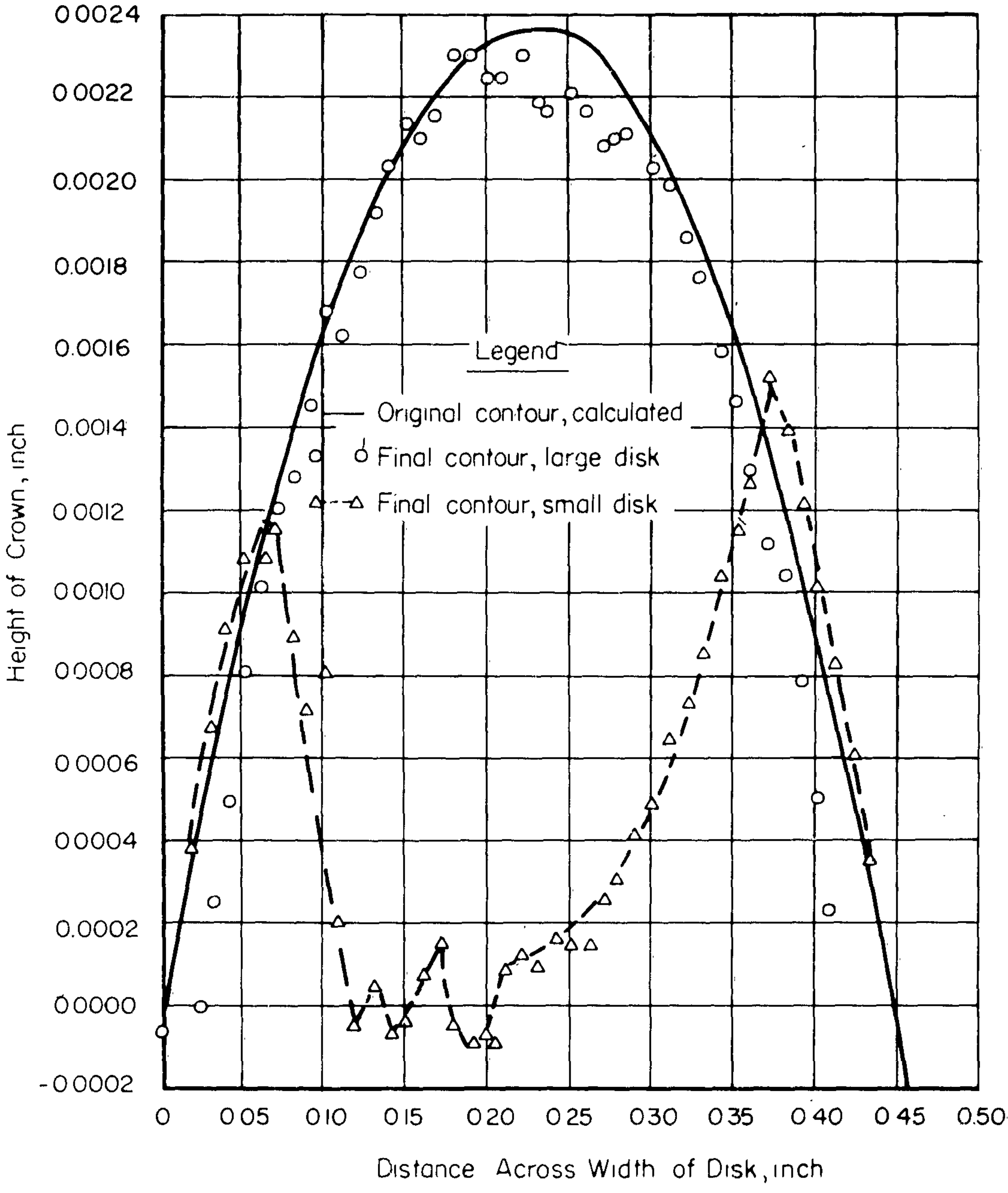

Figure A1. Contour Trace of Rene '41 Disks After Rolling-Contact Operation at 1000 F

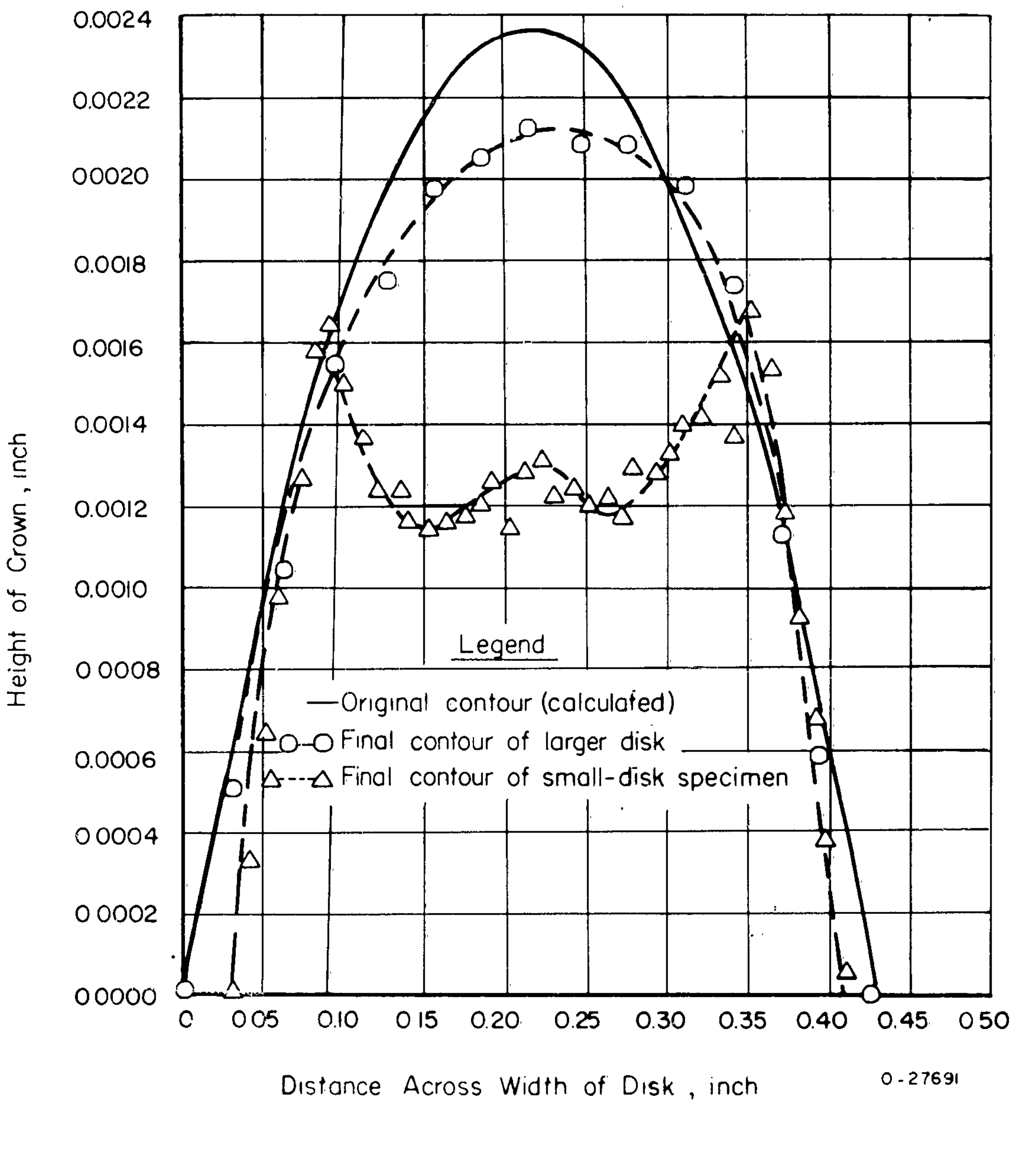

Figure A2. Contour Trace of Haynes Stellite 151 Disks After Rolling-Contact Operation at 1000 F

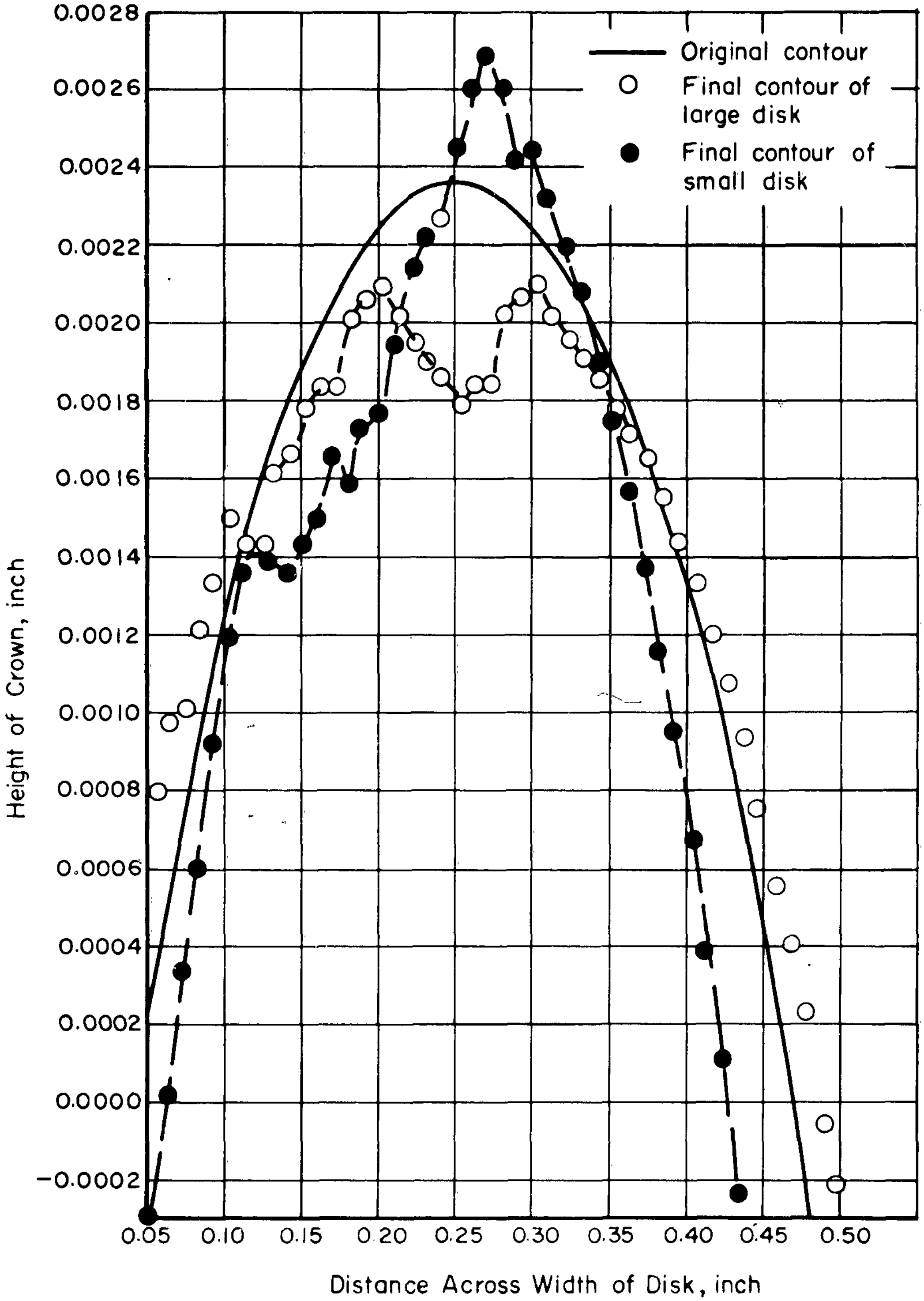

Figure A3. Contour Trace of Stellite 6B Disks After Rolling-Contact Operation at 1000 F

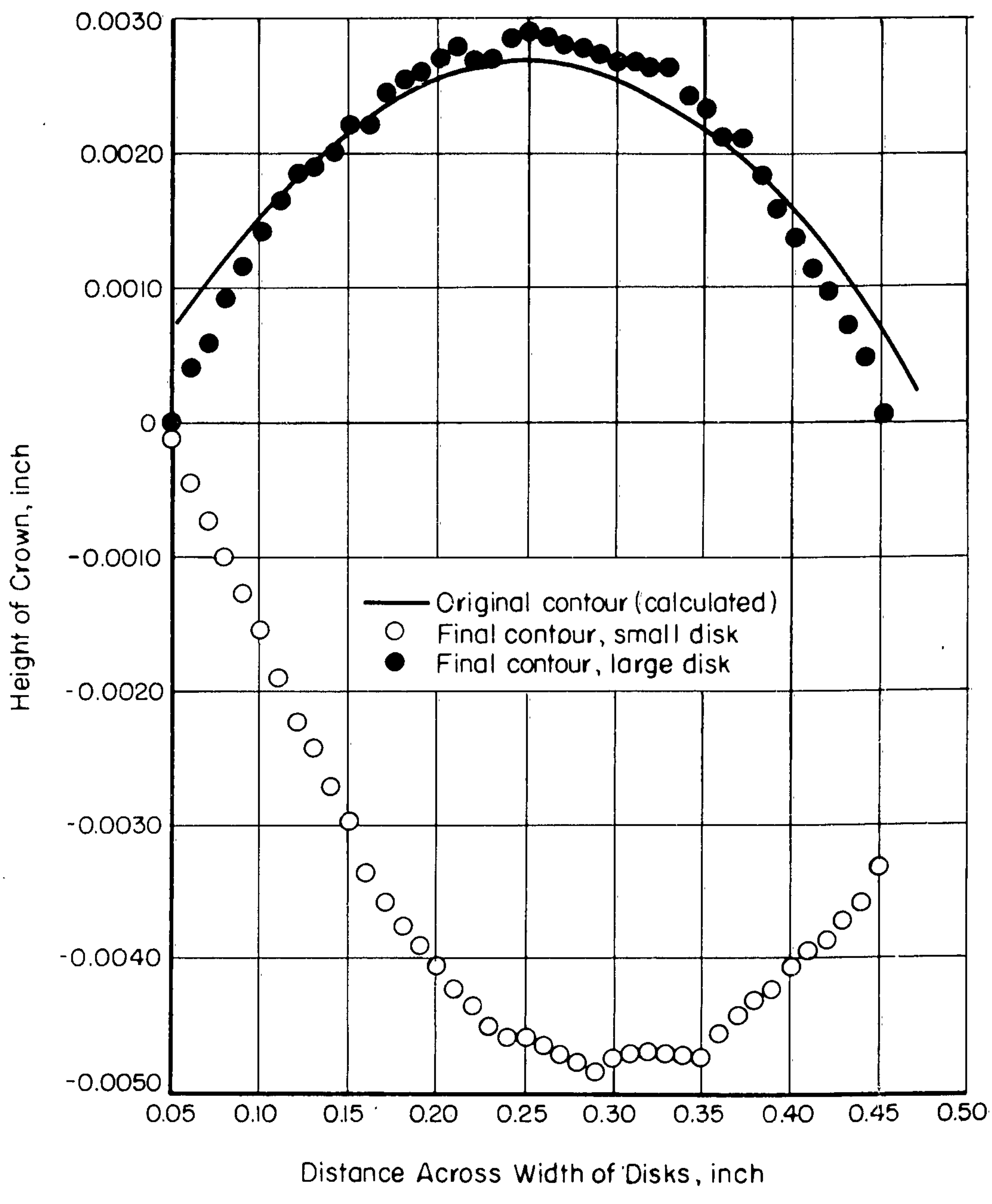

Figure A4. Contour Trace of Rene '41 Disks Coated with a Chromium Carbide Cermet After Rolling-Contact Operation at 1000 F

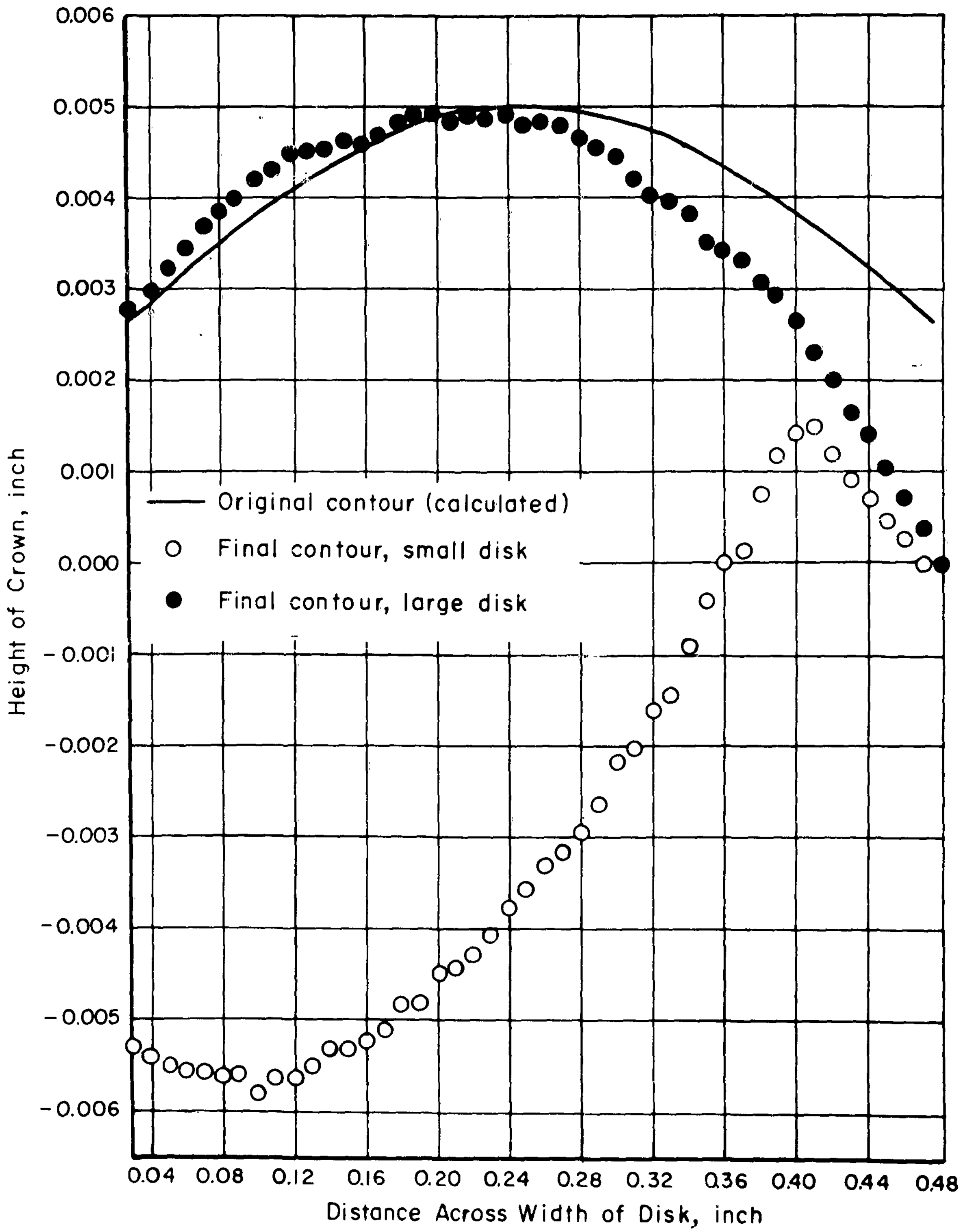

Figure A5. Contour Trace of M-50 Disks After Rolling-Contact Operation at 900 F